THE HIGH INTENSITY PROTON LINAC FOR CSNS

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Abstract

Work on the China Spallation Neutron Source (CSNS) has been progressing well, including successful prototyping of some of the key components of the facility. CSNS R&D projects of linac have extended to many aspects including the test stand of the H^- ion source, the pre-chopper in LEBT, prototype of DTL, RF system and beam diagnostics. The status of the R&D projects will be described.

INTRODUCTION

The accelerator for CSNS is composed of an 81 MeV H^- linear accelerator (linac) as the injector and a 1.6 GeV Rapid Cycling Synchrotron (RCS) with a 100 kW beam power for CSNS phase-I [1]. The 324 MHz linac consists of a 50 keV H^- Penning surface plasma ion source, a low beam energy transport line (LEBT), a 3.0 MeV Radio Frequency Quadrupole (RFQ) accelerator, a Medium Energy Beam Transport line (MEBT), an 81 MeV Alvarez-type Drift Tube Linear Accelerator (DTL). The output beam current of the linac is about 15 mA with a pulsed beam width about 500 μs and a repetition rate of 25Hz.

The ISIS Penning surface plasma H^- ion source is chosen as the ion source of CSNS for the following reasons [2]: (1) it completely satisfies the CSNS phase-I beam requirements; (2) it is the lowest cost compared to other types of ion source; (3) there is good collaboration between the Rutherford Appleton Laboratory (RAL) and Institute of High Energy Physics (IHEP). The extracted pulsed beam current of the ion source is 20mA with a normalized rms. emittance of 0.2 πmm.mrad.

The magnetic matching and focusing structure with three solenoids are adopts for CSNS LEBT to make full use of the effects of charge neutralization. An electrostatic deflector as the pre-chopper, which is installed downstream LEBT, i.e., the entrance of RFQ, is chosen to pre-chop the beam.

Four-vane type RFQ is adopted to accelerate the H^- beam from 50 keV to 3.0MeV. The length of RFQ is about 3.6m. The RFQ consists of two resonantly coupled sections, and each section includes two mechanical modules connecting together by flange. Although a pulsed beam current of 20mA for the RQF is required for CSNS phase-I, the RFQ is designed to transmit a beam with a pulsed current of 40mA for upgrade in future.

A high-duty factor proton RFQ accelerator has been constructed at IHEP, Beijing for the basic study of Accelerator Driven Sub-critical System (ADS). In the initial commissioning of the 3.5MeV RFQ with an electron cyclotron resonance ion source showed a nice performance with a transmission rate about 93% and an output beam current of 44.5mA. The 352.2MHz RFQ is basically design for CW operation with the RF power source from LEP-II of CERN. The beam commissioning afterwards has extended the beam duty factor to 15%.

MEBT with a chopper is designed to satisfy the CSNS upgrade requirement on a pulsed beam current of 40mA. MEBT is structurally similar to J-PARC MEBT due to the same exit energy of RFQ and similar DTL structure with J-PARC [3]. It mainly consists of 8 quadupoles, 2 bunchers and 1 chopper. In addition, two vacuum gate valves and a number of beam diagnostic components are also installed between or in the quadrupoles. 8 sets of steering magnets are incorporated into quadrupoles through wiring on the quadrupole yokes. For CSNS phase-I, only space is left for the chopper.

The DTL consists of four independent tanks with an average length of around 8.6 m for each tank, and each tank is further divided into three short unit tanks with about 2.8 m in length for easy manufacture [4]. The electromagnetic quadrupole (EMQ) is adopted to focus the beam transversely, and the total 156 EMQs is divided into two groups according to the yoke out diameter and the aperture of the magnet. The face angles of the drift tube increase from 0º to 60º to achieve the higher shunt impedance while keep enough space for housing the electric quadrupole magnets inside. The peak surface field always keeps below 1.3 Kilpatrick.

THE TEST STAND OF H^- ION SOURCE

R&D of CSNS H^- ion source started with the manufacture of the discharge chamber and the extraction electrode. The collaboration with RAL provided a complete set of mechanical drawings. Several sets of discharge chambers and extraction electrodes have been manufactured domestically. Tests with these discharge chambers and the extraction electrodes on the H^- ion source test stand at RAL demonstrated that the performance of these components is exactly the same or better than those made in the UK for ISIS. After the successful manufacture of the discharge chamber for the CSNS ion source, an H^- ion source test stand is constructed as one of CSNS R&D projects. The objectives of the H^- ion source R&D projects are, firstly to examine whether the performance of the discharge chamber in our test stand is the same as that in the RAL ion source test stand; and secondly to build a stable and

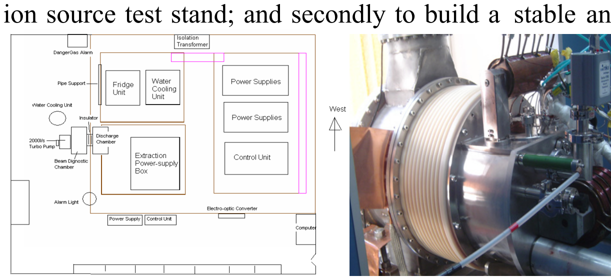

Figure 1: Schematic layout of the H^- ion source test stand and the ion source main body.

reliable ion source test stand to facilitate further improvement of the ion source for CSNS.

The schematic layout of the H^- ion source test stand in the laboratory and the ion source main body are shown in Fig.1. The construction of the H^- ion source test stand was finished at the end of 2009.

Commissioning of the source is in progress. Stable H^- ion beams with currents up to 50 mA and energies of 50 keV are achieved. Fig.2 shows the ion source commissioning results. The pulsed discharge current is about 50 A with a pulse width of 800 µs. The extraction current (both the H- ions and electrons) is about 300 mA with a pulse width of 520 µs. The pulsed discharge current is adjustable from about 30 A to 50 A, and the extraction current also varies with the discharge current. In this discharge state, the output H^- ion beam with energy of 50 keV and a current of 53 mA is achieved. The pulse H^- ion beam width is also 520 µs and the repetition rate is 25 Hz. 48 hours continuous operation of the test stand is also carried out, and more than 8 hours stable operation without interruption has been achieved. Emittance measurement of the beam is also being prepared.

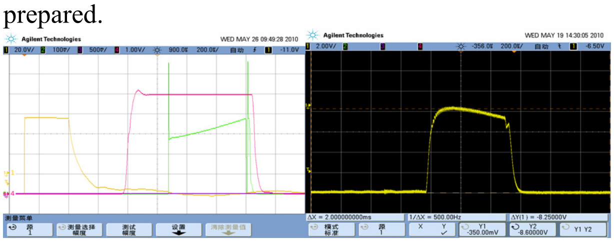

Figure 2: The H^- ion source commissioning results, left: pulsed discharge current (red) and the extraction beam current (green); the voltage output of the piezoelectric hydrogen valve power supply (yellow); Right: H^- ion beam current.

EXPERIMENT RESULTS OF THE PRE-CHOPPER IN ADS RFQ LEBT

In order to examine the reliability of the CSNS pre-chopping design, a similar pre-chopping design in the ADS RFQ LEBT is also done. The design is based on the existent ADS RFQ LEBT layout and the structure of the third vacuum chamber located at the entrance of RFQ. As shown in Fig.3, the deflector, the collimator and the electron-trapping electrode are all installed on the existent beam current monitor ACCT housed in the third vacuum chamber. The chopped beam is designed to lose in the RFQ cavity to lower the deflecting voltage and to save the beam target. The sloping deflecting plates instead of parallel deflecting plates are adopted to decrease the deflecting voltage. To lower the capacitance between the two plates, the width of the deflecting plates also varies with the envelope size. The horizontal length of the deflector is 50 mm, the gap between the deflecting plates varies from 20.16 mm to 33.84 mm, which is 1.2 times the beam envelope size, and the width of the deflecting plate varies from 25.2 mm to 42.3 mm, which is 1.5 times the beam envelope size. Simulations are carried out to determine the relationship between the RFQ transmission and the displacement and the deflecting angle of the input beam and thus the deflecting voltage through the RFQ multi-particle tracking code PARMTEQM. The beam transmission of RFQ is zero when the deflecting voltage is 3.16 kV.

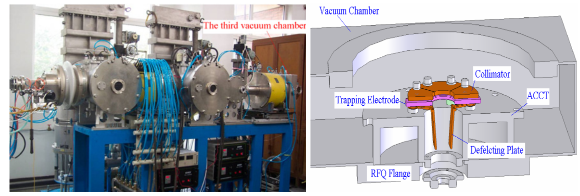

Figure 3: Layout of ADS RFQ LEBT (left); the deflector and relative components in the third vacuum chamber (right).

In chopping experiments, the macro pulse beam width increases from 100 µs to 500 µs and repetition rate increases from 1 Hz to 25 Hz gradually while the chopping rate of 50%, the chopped pulse beam width of 530 ns and the pulsed beam current of around 32 mA keeps constant all the time. The beam structure got in the last chopping experiment is basically the one required by RCS. The chopping results are examined by the Beam Position Monitor (BPM) located at the exit of RFQ. In Fig.4 and Fig.5, the chopping experiment results are shown.

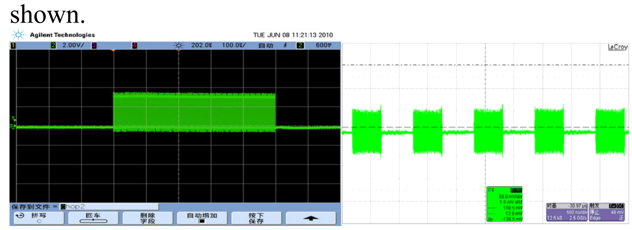

Figure 4: Chopping experiment results, left: the output voltage of the power supply (voltage of 4.5 kV, the macros pulse width of 500 µs, repetition rate of 25 Hz); right: beam signal of the BPM (chopping rate of 50%, micro pulse beam width of 530ns).

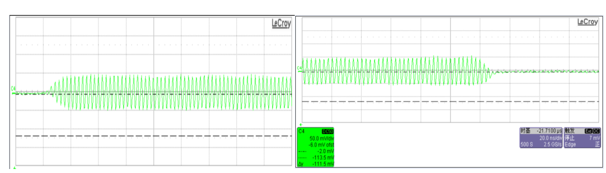

Figure 5: Beam signal detail of the BPM at the rise and fall time, both the rise and fall time are about 4-5 RF periods (a RF period is 2.84 ns).

STATUS OF DTL PROTOTYPE

The following items are chosen as the DTL R&D project: (1) manufacture of the first short unit tank; (2) manufacture of the 28 quadrupole magnets and (3) manufacture of the 28 drift tubes for the first short unit tank.

DTL Tank Manufacture

The tank is made of carbon steel tube with an inner diameter of 566 mm. The inner surface of the tank is coated with Oxygen Free Copper (OFC). The periodic reverse copper electroforming technology has been successfully applied for both inner surface and all ports/holes in the tank manufacture. Since the first unit DTL tank contains 9 large ports for tuners and vacuum, and approximate 60 small ports for drift-tubes, post couplers and pickups. It is rather complex to electroform the tank. In addition, there are still twelve straight water cooling channels embedding into the tank outside wall.

Figure 6 shows the first unit tank prototype module. The inner copper surface has been polished and the ports have been fine machined for high accuracy and high flatness. The measured inner surface flatness is in the range of 0.26~0.29 μm (the design value is 1.6 μm), and the average copper thickness is 0.2 mm (the design value is 0.15 mm). The measured inner diameter, the length and the positions of the DT ports are all within the error requirements. Up to now, the polish of the tank inner surface is finished and the washing will be carried out in this month.

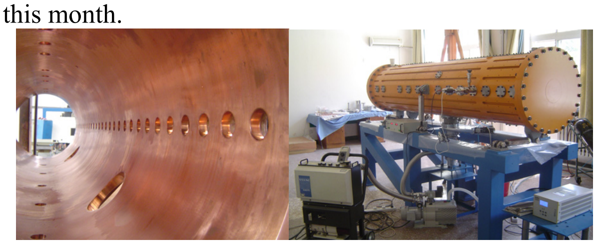

Figure 6: Prototype of the first unit DTL tank.

Electromagnet Quadrupole

The gradient of the EMQs is in the range from 75 T/m to 38 T/m. The outer diameter of the DT is 148 mm and the inner aperture diameter 12 mm while the width is only 49.89 mm in minimum. Because the size of the drift tube for the lower energy section of the DTL is so small that it is impossible to apply the standard techniques to manufacture a high gradient electromagnetic quadrupole and install it in the small DT. So the R&D of the quadrupole for this section of the DTL is a critical issue for the DTL structure. The SAKAE type coil is applied to solve this problem. Both the wire cutting and the periodic reverse copper electroforming methods are applied in the SAKAE type coil manufacture process.

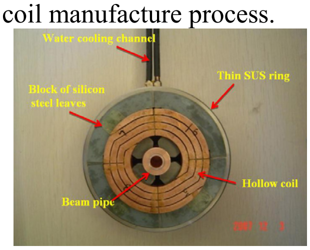

Figure 7: The EMQ assemblies.

Figure 7 shows the main components of the quadrupole. The silicon steel with a thickness of 0.5 mm is chosen as the core material. The yoke out diameter of the magnet is 118 mm and the magnet aperture 15 mm while the width of coil is 45 mm. After the assembly of the first prototype EMQ, field measurements are carried out by using Hall probe. The measured results are basically agreed with the calculated ones. For instance, the designed gradient of 75 T/m can be achieved with an excitation current of 495 A lower than that from 3D simulation. The measured effective length is 42.8 mm, which is a little longer than the design one by about 3.7%. The 28 EMQs have been fabricated and measured.

DT Fabrication

One of the main features of the CSNS DTL is the use of OFC for all parts of drift tubes. Long-term deformation test results convinced us the material selection and design. The fabrication process is a little complex since it is always accompanied by many tests and measurements.

The magnetic field of the EMQs is measured many times by using a rotating coil measurement system during the DT fabrication process. After the installation of the magnet into DT before welding, the first measurement is carried out for checking the deviation between the tube mechanical center and the quadrupole field center. In this stage, the required concentric tolerance is less than 50 μm. The mechanical center is adjusted to fit the field center by lathing the bore cylinder if the tolerance is larger than the required value. The second measurement is done after the tube shells, the beam pipe and the base of the stem are welded together by using EBW. Certainly, the magnet has been accommodated in DT at this time and the space around the magnet in the DT is filled with the epoxy resin by a vacuum impregnation method. The purpose of this measurement is also to get the discrepancy between the tube mechanical center and the quadrupole field center. Then the beam pipe and the tube cylinder are lathed in accordance with the magnetic center. The tolerable deviation between the mechanical center of DT from the magnetic field center is less than ±30 μm for the beam dynamics requirement. The last measurement is done after the completion of all the fabrication process. The purposes of the measurement are not only the confirmation of the magnet properties measured before but also the acquirement of the discrepancy data for alignment work.

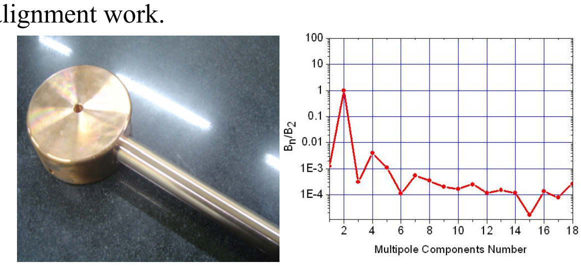

Figure 8: The first prototype of drift tube (left) and the measured higher-order components (right).

As shown in Fig.8, the first prototype of DT has been successfully fabricated in this January. The measured discrepancy between the drift tube mechanical center and the magnetic field center is 12 μm. The higher-order multipole components are sufficiently small and less than 0.3% in comparison with the quadrupole component. The batch manufacture of DTs is also in progress, the remanent DTs will be completed in this month.

R&D PROGRESS OF LINAC RF SYSTEM

Digital Low Level RF (LLRF) Prototype

By taking use of the RF power source of the ADS RFQ accelerator, R&D of a digital low level RF prototype for CSNS was carried out [5].

The block diagram of LLRF is shown in Fig.9. The field control is implemented by a combination of feedback (FB) and feed-forward (FF) algorithms. The two 14bit-ADCs (AD6645) and two 14bit-DACs (AD9764) are installed on FPGA board. The digital FB and FF is carried out by one chip of FPGA (STRATIX II series by ALTERA Co.). The DSP (C6000 series by TI Co.) is in charge of communications and translating values between I/Q and Amplitude/Phase. AD8345 chip was adopted as IQ modulator.

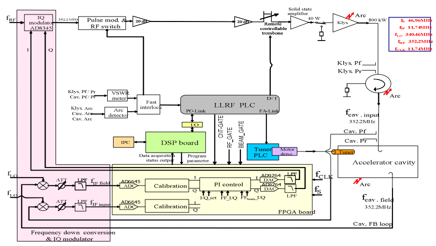

Figure 9: Block diagram of LLRF.

LLRF is tested well in ADS RFQ beam commissioning. As shown in Fig.10, with FB closed loop control, the fluctuations of the amplitude and phase at flattop are stabilized within ±1% and ±1 degree, respectively. The cavity RF field is highly flat. FF control can also effectively improve the transient response of the front and trailing edge of the beam loading. RFQ beam transmission is thus improved. Afterwards, during 48 hours continuous operation test, no LLRF control problem occurred and the stability was good.

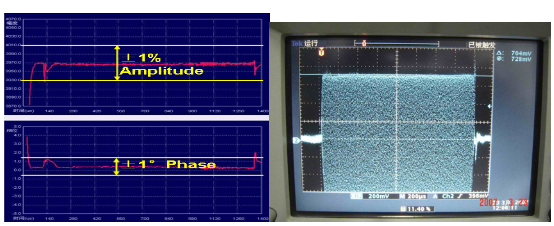

Figure 10: RFQ beam commission results with FB closed loop control: (right) cavity RF field signal, RF pulse width is 1.4 ms.

AC Series Resonance High Voltage Power Supply for Pulse Klystron

The schematic diagram of the proposed -120 kV /50 A high voltage power supply for pulse klystron is shown in Fig.11. Its basic features are AC series-resonant charging and pulse synchronized discharging. The resonant inductance L and the resonant capacitor C compose a series resonant circuit, and its natural resonance frequency is designed to 100 Hz. This scheme avoids step-up high voltage transformers and multiphase high voltage rectifiers. The circuit topology is very simple, so it should achieve a good operating reliability and low trip rate, thus be convenient for operation and maintenance.

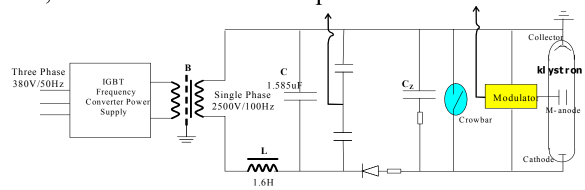

Figure 11: Proposed AC series resonance high voltage power supply for pulse klystron.

Prototype design parameters are L=1.6 H, C=1.585 μF, and inductance unloaded quality factor $Q_0 \geq 250$ is required. In this case, AC to DC efficiency is 87% by simulation. The prototype test results are quite satisfactory. The measured Q_0 value of inductance is no less than 350. On a test condition of klystron cathode voltage 66kV and output RF power 420kW, AC to DC conversion efficiency is up to 88%. The performance of the system built agrees with simulation results. Figure 12 shows AC resonant inductance and AC resonant capacitor. In Fig.13, the AC resonance charging voltage (the sinusoid wave) on AC resonant capacitor, the klystron modulation anode voltage (the discharging pulse trace) and the klystron output RF power are shown.

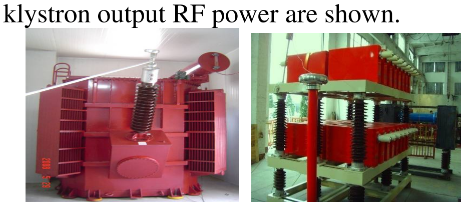

Figure 12: AC resonant inductance (left) and AC resonant capacitor (right).

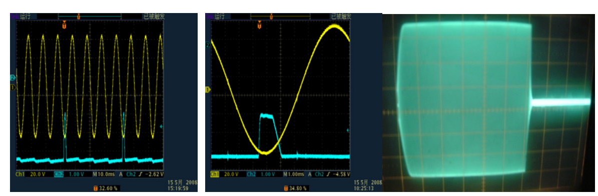

Figure 13: AC resonance charging voltage (left), the klystron modulation anode voltage (middle) and the klystron output RF power (right).

To reduce AC noise and volume of the components, a new design to increase AC resonance frequency up to 400Hz is ongoing. The parameters of inductance and capacitor are designed as 0.799 H and 0.198 μF.

Modulator and Crowbar

As shown in Fig.11, the high voltage DC power supply feeds a constant voltage to the klystron cathode. M-anode modulator generates an anode pulse voltage to control the output power of pulse klystron. The crowbar is a necessary high voltage fast protection device. In case of an arc occurring inside the klystron, the crowbar can remove the high voltage energy from the klystron and DC capacitor bank within a few microseconds to avoid the damage of the klystron.

M-Anode Modulator

The schematic, the internal and external structures of modulator prototype are shown in Fig.14. Klystron m-anode pulse voltage is generated by switching the cathode voltage through dividing resistors (R1 and R2) in the m-anode modulator. The anode voltage can be adjusted by the dividing ratio, and the pulse duration is controlled by a switch connected with the resistors in series. The switch from PEEC (a company in Japan) is the same as that of J-PARC modulator. It mainly consists of 150 FETs (Field Effect Transistors) in series configuration, and can withstand -120kV moment voltage. Unloaded high voltage test (no klystron load) is carried out on a condition of 25 Hz /110 kV /700 μs. As shown in Fig.15, the measured rise and fall time are 4.15 μs and 45 μs, respectively.

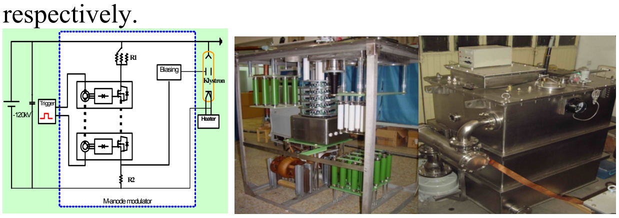

Figure 14: The schematic (left), the internal (middle) and external (right) structures of modulator prototype.

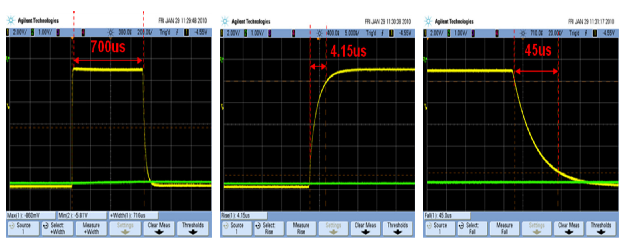

Figure 15: Unloaded high voltage test results: 700 μs m-anode pulse, 4.15 μs rise time and 45 μs fall time.

Crowbar

CSNS crowbar prototype is the one of ignitron type. The block diagram, the internal and external structures of crowbar prototype are shown in Fig.16. 7703EHVNP ignitron, made by Richardson in USA, serves as crowbar tube. Its peak anode voltage is 50kV and peak anode current is 100kA. Therefore, 4 ignitrons in series configuration are adopted. Each ignitron is driven by one sub-trigger module. The control signals of the four sub-modules are fed from a 4-output trigger module via glass optical fiber. As shown in Fig.17, a high voltage test stand is set up to carry out crowbar full voltage (-120kV) over current trigger-to-discharging test. The test result shows that the response delay time is 4.5μs, less than the design specification of 6 μs.

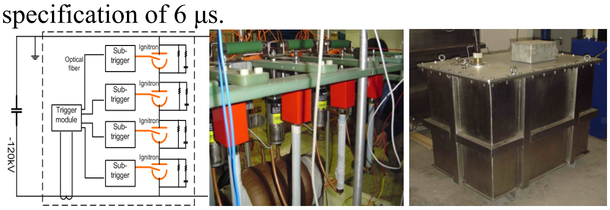

Figure 16: Block diagram (left), internal (middle) and external structure (right) of CSNS crowbar.

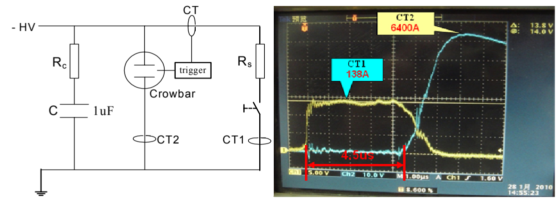

Figure 17: full voltage -120kV test: crowbar test circuit (left), delay time from triggering to discharging is 4.5 μs (right).

R&D OF BEAM DIAGNOSTIC COMPONETS

Two prototypes of the stripline type Beam Position Monotor (BPM) are manufactured and calibrated. The LR-BPM signal processing electronics of the Bergoz Company is adopted to perform the pulse beam measurement. As shown in Fig.18, The calibration of the prototype BPM is firstly carried out on a calibration test bench to find out the offset value and BPM sensitivity. The response of probe shows a good symmetry. As shown in Fig.4 and Fig.5, the two BPMS show a good response of beam in ADS RFQ commissioning experiments. In addition, the manufacture of the Beam Loss Monitor (BLM) and Wire Scan prototypes is also complete, tests of the prototype is in progress.

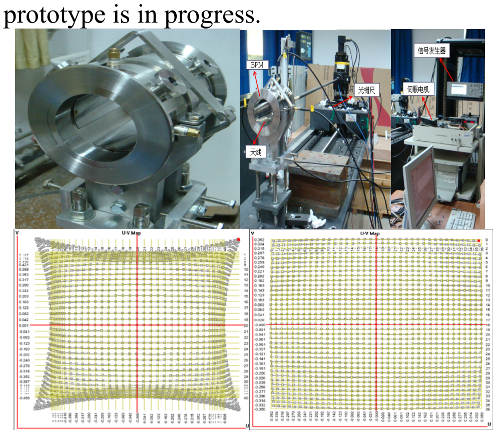

Figure 18: Prototype of BPM (above left), the calibration test bench (above right) and the calibrated results (below).

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