ACTIVITIES ON HEAVY ION RFQ AND RF SUPERCONDUCTING CAVITIES AT PEKING UNIVERSITY*

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Abstract
Progress on an Integrated Split Ring (ISR) RFQ with water-cooled mini vane electrodes was reported. N^+, O^+ and O^- ions have been accelerated to more than 300 KeV. The beam transmission efficiency of the RFQ reached more than 84% with an average current of ~38.4 μA. Feasibility study of accelerating both O^+ and O^- ion beams simultaneously in the same RFQ was also performed. An ISR RFQ for accelerating oxygen ion beam up to 1 MeV was designed and constructed. Two superconducting cavities with China made niobium were successfully manufactured and tested by the RF Superconductivity group. A DC photo cathode electron gun with a 2MeV superconducting booster and a Cu-Nb sputtering system have been designed, manufactured and installed. The feasibility of a heavy ion superconducting booster with sputtering Nb QWR cavities was studied in collaboration with CIAE for their proposed project of Beijing Radioactive Nuclear Beam Facility. Both SC and RFQ groups of PKU are collaborating with IHEP and CIAE for a new proposal of accelerator driven nuclear energy source.

1 HEAVY ION RFQ

The RFQ group of Peking University has engaged in developing ISR RFQ cavities for ion implantation. A 300 KeV cavity was developed and studied extensively with a series of beam tests. A 1 MeV cavity was designed and constructed. The main parameters of these two cavities are shown in Table 1.

Table 1. Main parameters of ISR RFQ

Energy (KeV)	300	1000
F_0 (MHz)	26	26
Charge/Mass	1/14	1/16
Win (KeV)	20	22
Wf (KeV)	300	1000
Diameter (cm)	50	70
Length (cm)	90	250
Vo (KV)	75	70
Duty factor	1/6	1/6

1.1 Beam Tests of a 300 KeV Cavity

The structure of an Integrated Split Ring (ISR) RFQ resonator operating at 26 MHz is shown in Fig. 1[1-3]. The whole structure is cooled by water flowing through the spiral tubes, supporting rings and quadruple mini-vane electrodes, so as to have high duty factor and hence high average beam current. The end section of the electrodes was specially shaped so as to minimize the end effect and to improve the transverse beam quality. The parameters of this RFQ are listed in Table 1. The RF power is fed from a linear power amplifier (XFD-D5) with maximum power output of 30 KW (CW) or 50 KW (1/6 duty factor) through a water-cooled loop. The amplitude of the field gradient in the RFQ cavity is stabilized by a feedback loop with a Double Balance Mixer.

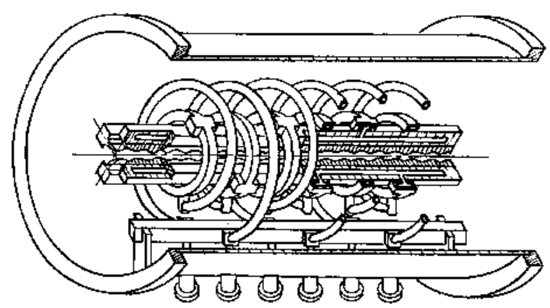

Fig. 1 View of a 26 MHz 300 KeV ISR RFQ

1.2 Layout of the Beam Test

The layout of the experiments is schematically shown in Fig. 2. The positive and negative ion sources are located at $\pm 45^0$ with respect to the beam axis. The ion beams extracted from both sources are focused by the Einzel lenses (EL) next to them. The ions can be either bent

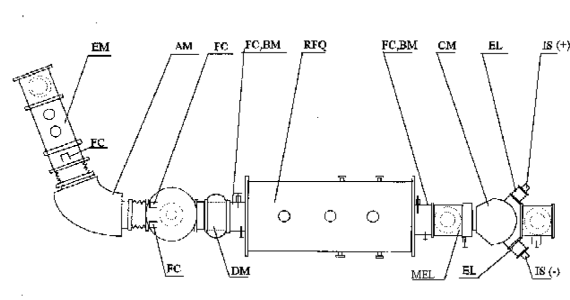

Fig. 2 Schematic layout of the experiment

separately or funneled simultaneously on to the beam axis by a combining magnet (CM) and then focused by a

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matching Einzel lens (MEL) in front of the RFQ. Two beam monitors (BM) are mounted at the RFQ entrance and exit respectively to measure the input and output beam intensity. The beam current after acceleration can also be measured by two off-axis cups (FC) with a small magnet (DM). The energy spectrum of the beam is measured by using the analyzing magnet (AM).

1.3 Acceleration of O^+, O^- and N^+ beams

Cold cathode PIG ion sources with permanent magnets are developed at our lab. The one used for producing O^+ ions is of side extraction type, while the other one for O^- ions is an end extraction sputtering type PIG ion source. The DC current of O^+ ions obtained at the entrance of the RFQ after a deflection of 45^0 ranges from 200-490 µA under an extraction voltage of 17-20 KV. The beam energy after acceleration is determined by the analyzing magnet and is shown in Fig.3 versus RF power. The highest energy gain of 306 KeV was reached at an RF power of 30 KW. The output beam is quite sensitive with the matching lens. The transmission efficiency increases with the vane voltage until it reaches the maximum value of 43%. With a duty cycle of 1/6, the highest average current measured was 17.5 µA, the DC equivalence of which is 105 µA and the corresponding microscopic peak current is estimated to be more than 1mA. The DC current of O^- beam obtained at the RFQ entrance was 175µA. The maximum of the transmission efficiency is more than 48% which seems to be a little higher than that of the positive ions. The voltage of the matching lens used was of 13 KV and the transmission efficiency tends to increase further with focusing voltage [4-6]. Since the aperture of the input cup is of 25 mm, which is considerably larger than that of the entrance diaphragm (15-mm) located at a distance 10 cm downstream. So the efficiency thus measured was quite underestimated. The location of the diaphragm and the input cup was swapped later for this reason and the beam efficiency for the N^+ beam raised to 78%.

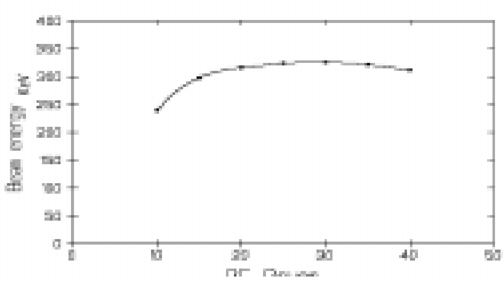

Fig. 3 Beam energy of O^- versus RF power

Acceleration of O^+ Beam was also performed in a pulsed ion source mode. The arc voltage of the source is triggered and synchronized with the RF modulation with a frequency of 166 Hz and the duration of the pulse can be adjusted by the trigger signal. The waveforms of the input and output beam current are recorded on a digital oscilloscope as shown in Fig.4. The peak current of I_i and I_o are 330 µA and 280 µA respectively at an input RF power of 45 KW, which indicates a beam efficiency of 84.3 %. The trigger time can also be shifted to change the time acceptance for acceleration. The merit of a pulsed mode operation lies both in enhancing peak arc power as well as in eliminating background of non-accelerated ions.

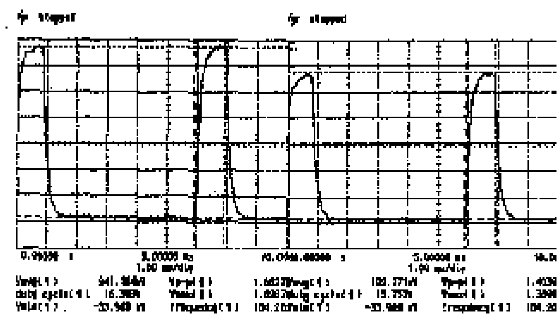

Fig.4 Pulse form of input and accelerated beam.

1.4 Simultaneous Acceleration of O^+ and O^-

Simultaneous acceleration of both O^+ and O^- ions in the same RFQ was tested. The ion sources and the focusing lenses related should be set according to their own characteristics. The extraction voltage for O^+ is normally ~ 20 KV, while for O^- is limited to 17 KV because of sparking. However, the optimum voltage of the matching lens for O^+ is about 11 KV while it should be ~18 KV for O^- ions. So the voltage setting has to be a kind of trade off, and 13 KV was chosen for the first trial. The simultaneous acceleration was performed at various RF power levels with the average current output varied from 0.1 to 21 µA under a duty factor of 1/6. The current ratio of O^+ to O^- varied from 0.1 to 5. The sum of O^+ and O^- current for simultaneous acceleration I_{sim} is compared with that of I_{sep} where O^+ and O^- were accelerated separately under the same condition in all cases. It appears that I_{sim} is about the same as I_{sep} in all the current ranges as can be seen from Fig. 5. This means that both positive

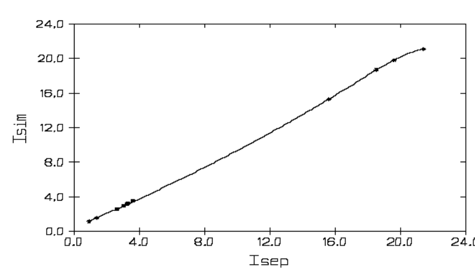

Fig.5 I_{sim} vs. I_{sep}

and negative half period of the RF cycle can be used to accelerate corresponding sign of ions at the same time. The interactions between negative and positive ion bunches are negligible, so far as the micro-peak current concerned is of order of ~1 mA, as it was expected. It is also worth mentioning that the result implies that dual species of ions of different amount can be implanted at once with deliberate ratio by using the present set-up [7].

1.5 Heavy ion ISR RFQ of 1 MeV

A 1 MeV heavy ion RFQ is being built based on the above experiences. The main parameters of which are listed in Table 1. The cavity tank has been designed and constructed. The mini-vanes and its supporting arms are mounted on the bottom plate with a movable cover so that they can be accessed and set up easily as shown in Fig.6. The water-cooled vanes are made of Cr-copper so as to reinforce its rigidity. They are being machined with 2-dimensional cutting by an NC mill. The vacuum of the cavity tank has already reached 2.5×10^{-6} Torr. The high power and beam tests are expected to be carried out by the end of 1998.

Fig. 6 The Cavity tank of 1 MeV RFQ

2. ACTIVITIES ON RF SUPERCONDUCTIVITY

The SC group of Peking University has been quite active in studying RF superconductivity since 1988. Treatments and tests on an L-band Nb cavity from DESY were accomplished in 1991[8]. Two superconducting cavities with China made niobium were then successfully manufactured and tested [9] by the end of 1994. To meet the requirements of high brightness electron beam for short wave Free Electron Lasers, Linear Colliders and etc., the SC Group at PKU is interested in developing high brightness electron beam source. As a first step, a laser driven photo-cathode DC electron gun with superconducting booster cavity is constructed [10]. Meanwhile, Cu-Nb sputtered QWR is being developed in collaboration with CIAE [11]. A proposal on Beijing Radioactive Nuclear Beam Facility (BRNBF), which is based on a cyclotron injector, an HI-13 tandem accelerator and a superconducting QWR booster, was submitted [12]. Therefore, a DC Cu-Nb sputtering system was constructed and installed at PKU for this purpose.

2.1 Photo-cathode electron gun with a 2MeV SC booster

A laser driven DC electron gun and a superconducting booster were constructed and installed at PKU. A high-gradient DC field extracts the electrons generated at the photo-cathode and an SC accelerating section followed accelerates the beam to ~2 MeV. In this way, it was expected to provide Pico-second or Femto-second high brightness electron beam either in CW or pulsed mode. Polarized beam might also be available with special photo-cathode. Fig.7 is the layout of the whole system. It consists of five main parts, the photo-cathode preparation chamber, the DC acceleration chamber, the mode-locked laser, SC energy booster and the beam diagnostic system.

The unique feature of the photo-cathode preparation chamber is its capability of fabricating photo-cathodes by three different schemes, including ion implantation, CVD, and ion beam enhanced deposition. A Cs ion source is attached to the photo-cathode preparation chamber for implanting Cs ions to metal substrates without destroying the vacuum. It can generate Cs ions with a current of over 100 μA, the maximum implantation energy is 25keV.

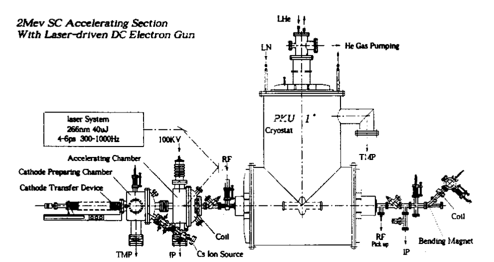

Fig.7 The layout of the High Brightness Electron Beam Source at Peking University.

The photo-cathode thus processed will be transferred from the preparation site to the DC acceleration chamber located 60 cm downstream via the photo-cathode load-lock system under high vacuum. This will avoid the contamination of the cathode surface and ensure good quantum efficiency. A number of cesium telluride photo-cathodes have been successfully fabricated with CVD scheme inside the preparation chamber. Now we are going to study the feasibility of Mg and Mo material as the substrate. The purpose is to improve the quantum efficiency of both metals and acquire photo-cathodes with longer lifetime. Fig. 8 shows the photograph of the cathode preparation chamber with a Cs ion source.

The mode-locked Nd-YAG laser system is able to provide laser pulses of 10 μJ at a wavelength of 266 nm and a pulse duration of 30-100ps with 1-10Hz repetition frequency. The electron beam is generated by the photo cathode located at the center of a DC focusing electrode system. Electrons are to be extracted at a voltage of ~100 KV and then accelerated up to about 2 MeV in a superconducting accelerating section consisting of 1.5GHz Nb cavities.

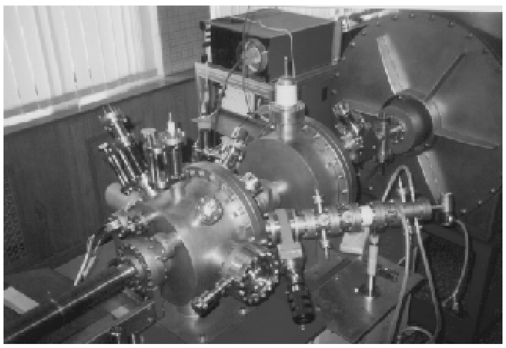

Fig. 8 Cathode preparing chamber with Cs ion source

Preliminary beam tests were performed with an extraction voltage of 45 KV applied to the cathode. Beam pulses of about 35 ps of ~0.05 nC was measured by a coaxial Faraday cup right after the extraction. The preliminary emittance measurement of the gun was carried out by the pepper-pot technique. It is shown that the emittance of the electron beam was in the range of 0.5-2 πmm-mrad, and the brightness was estimated to be as high as 5×10^{10} A/m^2 -rad^2 correspondingly.

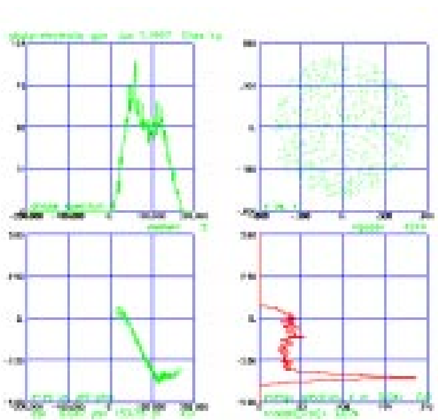

Fig. 9 Results of the simulation with PARMELA

To study the beam dynamics of the DC electron gun, we use the program PAEMELA to simulate the transportation of the beam and get the pulse duration, energy spread and emittance of the electron beam after the acceleration. Fig. 9 shows the pulse duration, energy spread and emittance at 100kV accelerating voltage, the total charge under consideration is 150 pC. The simulation shows that when the accelerating voltage is raised from 45kV to 100kV, the pulse duration will change from 160ps to 70ps. For the next step, we will develop an RF microwave photo-cathode electron gun of 1+1/2 cell-cavity to obtain pulsed electron beam with a duration of 2-6ps, peak current of over 100A and emittance of better than 1π-mm-mrad. This requires a high performance laser generator, which can produce 100fs-4ps pulse at peak energy of 40μJ with a repetition rate of 360Hz.

2.2 Efforts on Nb sputtered Cu cavities

As for the material of the quarter wave resonator (QWR) booster cavity, niobium is considered as having good mechanical properties but low thermal conductivity, which might induce thermal instability and thus increase the danger of quench. One effective way to tackle with the problem is to sputter a layer of high pure niobium, about several microns thick, onto the surface of the OFHC copper cavity, so as to increase the thermal conductivity by about ten times more than the pure Nb cavity at low temperature. For this reason, the niobium-sputtered copper QWR is the first choice as the post-accelerating structure for BRNBF, since it has good thermal conductivity, low price and is easy to manufacture. A number of experiments and tests on niobium-sputtered copper quarter wave resonators have been carried out since 1996. Great progress has been made in recent years, however it is really difficult to control the quality of the niobium films.

The sputtering system of Peking University consists of sputtering chamber, vacuum system, and gas control system as well as residual gas analysis system. Fig. 10 is the layout of the whole system. The main part of the system is a UHV chamber, 120cm in height and 60cm in diameter. A background vacuum of 2×10^{-7} Pa can be reached inside the chamber and a residual gas analyzer is set up with the chamber. A 12.5 KW DC constant current power supply is available for the sputtering.

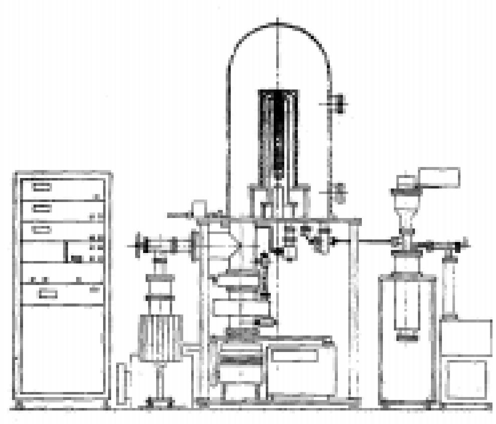

Fig. 10 Layout of the Nb-Cu sputtering system

The configuration of the QWR is optimized with the program MAFIA with the joint efforts of both CIAE and Peking University. Fig. 11 is the configuration of the resonator. One aluminum model QWR was then manufactured. A series of efforts has been made to get a homogeneous Nb film on the QWR geometry surface. First we manufactured an aluminum cavity and copper target. This was used to observe the state of discharge and to test if the system works normally. By sputtering copper to the surface of the Al resonator under various conditions, we managed to define the geometrical dimensions of the target and sputtering parameters as well. We used probing samples of glass to test the properties of the film and the result is promising. The homogeneity of the film is good, the ratio of the thickness of the films on the inner conductor and the outer wall is quite close to 1.

Since Al cavity and Cu target cannot stand too high temperature, we use stainless steel QWR and target in the second step. It might reflect the niobium sputtering process more realistically. The film thickness and the structure of the contents were measured with glass probes under different parameters for many times. At the same time, the copper resonator and the niobium target was fabricated. The RRR of the niobium on the sample is also to be measured by a system including a 50-liter volume liquid helium cryostat. The niobium target is made with electron beam welding and the copper resonator is to be manufactured without welding seam. Glass probes were used again to test the homogeneity of the niobium film and it turned out that the film thickness on the glass samples is quite uniform from the bottom to the upper round corner. The sputtering parameters are: current of 1.7A, voltage of 1kV and Ar pressure of 22Pa. The film is produced by multiple pulse-discharges. The thickness is about 1μm. The difference of the thickness between the outer wall and the inner conductor is less than 20%, and the difference between the upper and the bottom part is less than 10%. Now, the OFHC resonator has already been manufactured. When the niobium-sputtered QWR is ready, we will do the test under low temperature and with beam load at our 2×6 MV tandem accelerator site so as to examine the performance of the prototype SC QWR.

3 CONCLUSION

Both the RFQ and SC groups of PKU have made considerable progress in developing ISR RFQ and superconducting accelerators in China. Recently CIAE and IHEP as well as PKU have jointly proposed a new project to promote the feasibility study on a 1GeV 10-30 mA proton accelerator so as to step into the field of Accelerator Driven Nuclear Energy Source or ATW. The RFQ should then be developed for the low energy acceleration section, while the SC could serve for high-energy acceleration.

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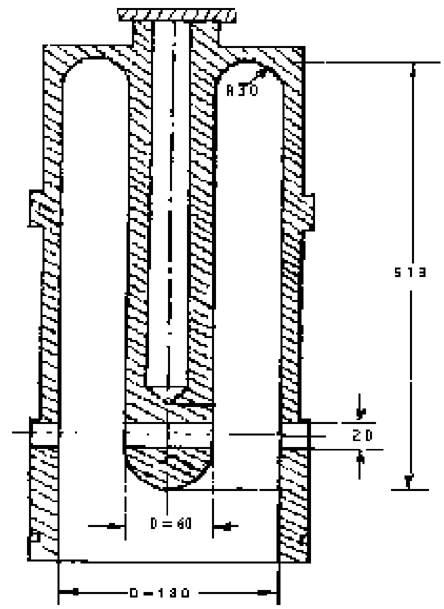

Fig. 11 The optimizing of the OFHC resonator.

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