PROGRESS OF RFQ AND SUPERCONDUCTING ACCELERATORS AT PEKING UNIVERSITY*

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Abstract

Efforts for developing RFQ accelerators of heavy ions and protons with high average current at Peking University are presented. Heavy ions are accelerated to 1 MeV with an average output current of ~100 μA by an Integrated Split-ring Resonator RFQ at an input RF power of 24 KW. The design study on a prototype high average current RFQ for protons is outlined too.

Efforts of developing electron and heavy ion superconducting accelerators in the past 10 years are briefed. A novel DC-SC photocathode injector is being developed and a 20~35 MeV superconducting accelerator, PKU-SCAF, is proposed. It is expected to work in CW mode capable of providing high average current (1~5mA) electron beams. An Nb-Cu sputtered QWR with a gradient up to ~6 MV/m in the 4.2k RF tests and 3 MV/m in the stable beam acceleration is reported.

1 INTRODUCTION

The RFQ accelerator, which was proposed by Kapchinskkij and Teplyakov in 1970, is experiencing a rapid development nowadays. The extensive interests in Accelerator Driven Energy Sources (ADS), Spallation Neutron Sources and other applications drive the RFQ developing towards high average beam power [1]-[3]. The Peking University RFQ group has been engaged in developing Integrated Split-ring Resonator RFQ (ISR RFQ) since 1984, to meet the needs of ion implantation and other applications of high average beam current [4]. A 300 keV heavy ion ISR RFQ was constructed and put into operation in 1994, where N^+, O^+ and O^- beam were accelerated with transmission efficiency better than 84%. The two-dimensional cutting mini-vane structure was developed then, which features with high mechanical rigidity and efficient inner cooling channel, and hence it enables the stable operation of ISR-300 at a duty factor higher than 16.7 % [5]. The RFQ was used to some extent as a test bench, where experiments of simultaneous acceleration of positive and negative ions in the same RFQ were performed and interesting results obtained [6][7]. Based on these experiences, the ISR-1000 RFQ was constructed and put into operation. It accelerates Oxygen beam to 1 MeV with an average current output of >100 μA with high RF efficiency and stability. The performance of the RFQ, including results on simultaneous acceleration of both positive and negative ions, as well as applications in material modifications is presented [8].

Feasibility studies on high beam power proton RFQ accelerator were initiated in 1998 to meet the needs of the ADS proposal [9]. The PKU group is collaborating with IHEP and CIAE to develop a 4-vane RFQ structure for this purpose. A prototype HPP-RFQ model has been designed and under construction. The working parameters of the model will be described.

With the support of the High Tech Program, efforts in developing electron and heavy ion superconducting accelerators in China have been progressing continuously ever since 1988. Two L-band SC cavities with China-made Nb was constructed and tested successfully in 1994. The accelerating gradient reached 10 MV/m with a Q_0 of 1010 [10]. To meet the requirements of high average power Free Electron Laser, a novel DC-SC photocathode injector is being developed on the base of a DC photocathode electron gun studied since 1999 [11]. It is proposed that a 20~35MeV superconducting accelerator facility, PKU SCAF [12], capable providing CW mode electron beams with high average current (1~5mA), should be installed at IHIP PKU. Meanwhile, PKU and CIAE are carrying out feasibility studies on the heavy ion superconducting energy booster jointly for the Proposal of Beijing Radioactive Nuclear Beam Facility [13]. By the end of 1999 an Nb sputtered copper QWR booster cavity was constructed [14]. A gradient up to 6 MV/m was reached in the RF tests at 4.2 K. The accelerating gradient of the QWR reached 3 MV/m in the stable operation with beam loading, where the proton beam was used to simulate the medium beta heavy ions.

2 HEAVY ION AND PROTON RFQ

Heavy ion RFQ is much preferable to operate at low frequency so as to get high beam current. Based on the studies of the integral split ring (ISR) type resonator [4], two ISR RFQ accelerators have been constructed at PKU. It turns out that this type of RFQ suits well for heavy ion acceleration as it has high RF efficiency at low operating frequency with good stability. A 26 MHz prototype RFQ for 300 keV N^+ ions (ISR RFQ-300) was first designed and constructed. The main parameters are listed at Table 1. The RFQ was tested to full power successfully with N^+, O^+, and O^- beams [5]. In order to enhance the total number of ions accelerated in one RF cycle, and to compensate at least partially the space charge both in the process of injection as well as on the target, a test bench capable of accelerating both positive and negative ions simultaneously in one RFQ was constructed [6] –[7] and the feasibility study was

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Table 1: Main Parameters of PKU RFQs

Type	ISR-300	ISR-1000
Ions	N^+ O^+ O^-	N^+ O^+ O^-
F_0 [MHz]	26	26
W_{in} [keV]	20	22
W_f [keV]	300	1000
I_{avr} [μA]	38.4	~100
I_p [mA]	~1	5
L [cm]	90	260
D [cm]	50	75
V_o [kV]	75	70
Duty Factor	16.7%	16.7%

carried out. The result shows that both the positive and negative half of a RF period accelerate the ions of corresponding sign in the same RFQ. The interactions between the positive and negative ion bunches can be negligible if the micro peak current is in the order of several mA [7].

Based on these experiences, a 26 MHz RFQ (ISR RFQ-1000) was constructed for implanting 1 MeV O^+ and O^- ions [8]. The dynamics design is shown in Fig. 1 and main parameters are also listed in Table 1.

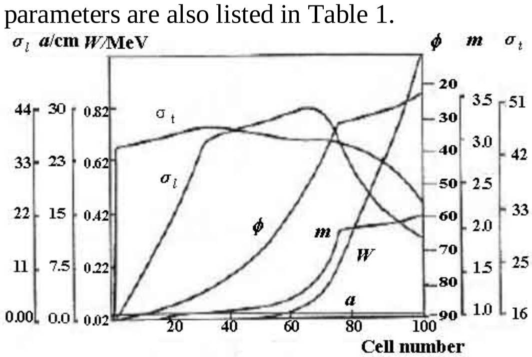

Fig. 1 Parameters of ISR RFQ-1000

The structure of the resonator is shown in Fig. 2. The tank of which is 2.6 meter in length and 75 cm in diameter. It consists of a bottom plate and an upper cover. The supporting arms are directly fixed on to the bottom plate, and the cover can be lifted freely for adjusting either the quadrupole electrodes or the supporting arms. The cooling water from the leg port flows through the arms and electrodes so as to ensure the high duty factor i.e. 1/6 or higher. The quadrupole electrodes are made of Cr-Cooper in the form of mini-vanes of two-dimensional cutting. The tip of the electrodes has a constant circular cross section with a radius R=1.0 cm which is 1.125 times the characteristic radius of RFQ so that the difference of focusing characteristics between the mini-vanes and ideal vanes reduces to a minimum [15].

It turns out that the ISR RFQ-1000 has a rather high RF efficiency. The Q-value is 3450 while the shunt impedance Rp and the specific shunt impedance ρ are 205 kΩ and 522 kΩm respectively. The working voltage of 70 kV is reached at an input power of 24 kW and the O^- beam was accelerated to 1 MeV with a peak output beam current of


Fig. 2 Structure of ISR RFQ-1000

660 μA and a beam efficiency of 83%, while for N^+ and O^+ ions, they are 300 μA and 320 μA respectively, both with an efficiency of 86 %. Detailed results are shown in Tab. 2.

Table 2: Detailed results of the beam test

Ion	I_{arc} mA	V_{arc} V	V_{ex} kV	P_{rf} kW	I_1 μA	I_2 μA	η %
O^+	250	1250	22.0	25.0	370	320	86.5
O^+	200	1100	22.0	25.0	240	210	87.5
O^-	300	1350	25.1	25.0	800	660	82.5
O^-	200	1100	25.0	25.0	670	570	85.0
N^+	300	1450	22.3	25.0	350	300	85.7
N^+	200	1100	22.0	25.0	230	200	87.0

In order to understand the performance of ISR-1000, the PARMTEQ was modified to enable adjusting input parameters, e.g. input energy and initial energy spread ε, inter-vane voltage V and etc. [16]. Interesting results on the output beam spectrum and transmission efficiency versus ε and V were obtained. Examples are shown in fig. 3 and 4.

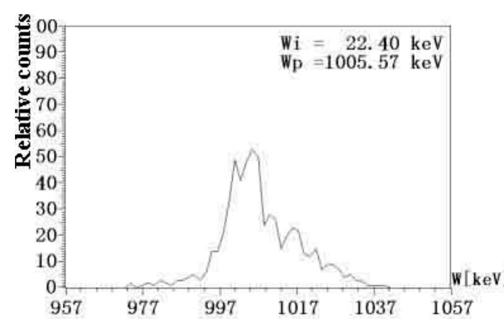

Fig 3. Energy Spectrum of output beam with ε=0

It appears that the measured spectrum (see Fig.5) is well in consistent with the case of ε = 0.1. While it is seen in Fig. 6, that the inconsistency in transmission efficiency

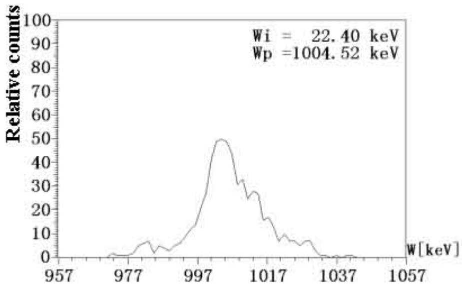

Fig 4. Energy Spectrum of output beam with ε=0.1

between the calculated and measured one might mean that there are ions other than the defined initial condition going through the cavity.

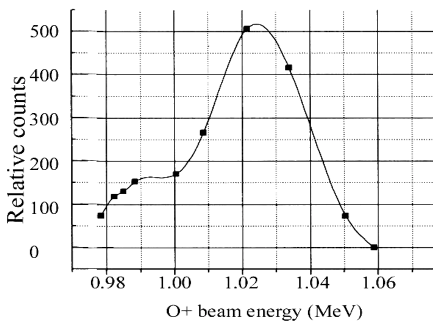

Fig. 5 Measured beam energy spectra of O^+

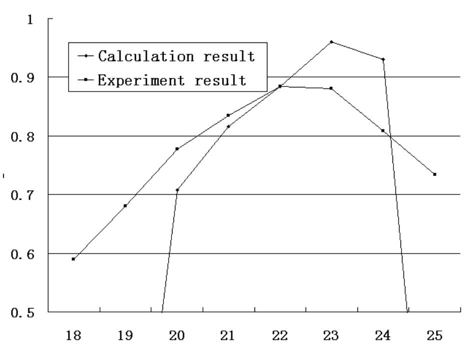

Fig.6 Beam efficiency versus input energy of O^+

Simultaneous acceleration of both O^+ and O^- ions has also successfully performed on ISR-1000. Ions of different signs from two permanent magnet PIG sources are injected into the RFQ through a combining magnet. However, differences in the beam quality between two sources cause difficulties in optimisation. Typical experiment shows when the beam transport setting is optimised for the output of O^-; the transmission efficiencies are 65% (640 μA) for O^- and 74% (170 μA) for O^+ respectively, while if optimised for O^+, the efficiencies are 34% (120 μA) for O^- and 88% (300 μA) for O^+. To fix the problem, the ion sources as well as the injection beam transport system are to be upgraded.

The RFQ is now available for applications. For example, samples of BN from SINR are irradiated with 910 keV N^+ ion beam to a dose of 3×10^{18} N^+/cm^2 for the study of material structures [17].

In addition to the heavy ion ISR RFQ, the four-vane type RFQ is also being studied to meet the requirements of the 150 MeV HPPA test facility. It is designated to accelerate more than 50mA peak current of proton beam (3 mA in average) to 5 MeV, with an input energy of 80 keV. It will be composed of three segments joining together with two coupling plates and an overall length of 7.1 meters. As a preliminary step, a test model of 118 cm long

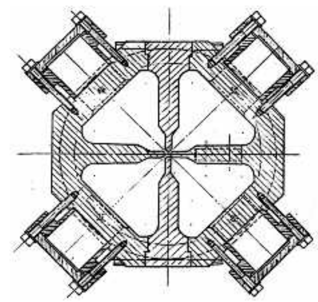

Fig.7 The Cross section of the test model

was designed and is under construction, so as to study the parameters and field distribution as well as the fabricating technology.

3 SUPERCONDUCTING CAVITIES

The laboratory on RF superconductivity at Peking University was established in 1988, and the PKU SC group has been active since then. With the kind offer of Dr. Proch, an L-band Nb cavity was sent to the laboratory from DESY to enable the first experiment on surface treatment and RF test. The field gradient reached more than 11 MV/m without Q degradation after a number of cycling in 1991 [18]. Two superconducting cavities with China made niobium were then successfully constructed. Special technologies such as the electron beam welding and heat treatments for Nb sheets were developed at this stage [10]. One of the difficulties associated with the Nb sheet was the low RRR value ranging from 50 to 60. With the help of Dr. P. Kneisel of TJNL, the RRR value was raised to 470 after it was treated with high temperature (~1400^0C). In the light of above success, one of the cavities was sent to KEK for heat treatment. The RRR of this cavity reached more than 270 and the field gradient increased from 4.5MV/m to more than 12MV/m, while the Q_0 value from 3×10^8 to more than 10^9, after the treatment helped by Dr. T. Furuya, and Dr. K. Saito. The Q versus E was verified at 1.8K by Dr. Kneisel in 1994 [10].

To meet the requirements of high average power Free Electron Lasers, efforts were made for developing high average current electron source with high beam brightness. As a first step, a laser driven photocathode DC electron gun [11] was constructed and studied. Electron beams in the range of 0.5-2 πmm-mrad, with a brightness of 5×10^{10} A/m^2 -rad^2 were obtained. To reduce the bunch stretch, a new DC gun with a superconducting cavity was proposed and designed [19].

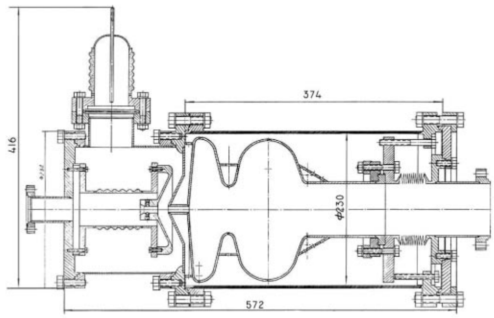

Fig. 8 Configuration of the DC-SC injector

The new laser driven DC-SC injector mainly consists of a high voltage Pierce electron gun followed by a 1+1/2-cell superconducting cavity (Fig. 8). The electrons generated at the photocathode are extracted by a high gradient DC field and accelerated by the cavity. One of the essential features of the design is to set the cathode outside the cavity so as to solve the problem of compatibility between the cathode and the SC cavity. As the distance between the cathode and the strong cavity field is very short, the growth of the emittance is not serious. The longitudinal compression is also performed by the phase focusing in the SC section.

The photocathode of the injector will be a p-type GaAs (Cs). The cathode of negative electron affinity is preferred because of its high quantum efficiency, typically 15% at 780 nm at a field gradient of 30 MV/m. The cathode will be prepared outside the gun structure, and be transferred to its operating position through a load lock system, where the vacuum is better than 10^{-11}Torr. By doing so we hope that the lifetime could be long enough to fulfil the practical need of a DC-SC photocathode injector. Since the injector is to be operated in CW mode, a frequency-doubled all solid-state Nd:YLF laser with an energy of ~10 nJ/pulse and a repetition rate of 30~40 MHz is being prepared. The DC-SC injector can also work with Mg-cathode driven by a UV laser, at a repetition of 1-100 Hz. Nowadays, the quantum efficiency of Mg shows a dramatic improvement through laser cleaning. It increases from 10^{-5} to 4×10^{-4} after two hours of cleaning, and to 2×10^{-3} after systematic cleaning [20].

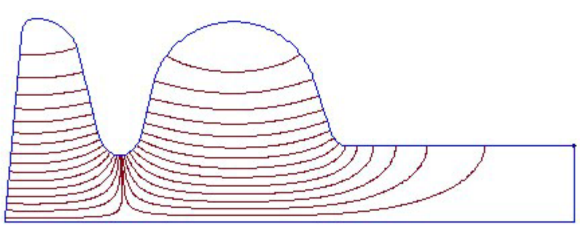

Fig. 9 The Field distribution of the injector cavity

The shape of the 1+1/2-cell cavity is optimised to minimize E_p/E_{acc}, while the Code PARMELA is used to calculate the performance of the whole injector [19]. Fig. 9 shows the electric field distribution in the cavity. The initial conditions and the results of simulation at the exit of the injector are listed in Table 4.

Table 4 : The simulation of the gun performance

Initial conditions		
Electron bunch	Radius	3.0 mm
	Length	10 ps
	Charge	60 pC
	Emittance	0 mm-mrad
SC cavity	Average gradient	15 MV/m
Pierce gun	Distance between cathode and anode	15 mm
	Cathode voltage	-70 kV
	Anode voltage	0 kV
Simulation results		
Anode inclination	65°	
Synchronous phase	-50°	
Energy	2.43 MeV	
Radius	2.8 mm	
$\Delta E_k/E_k$ (rms)	2.63%	
Bunch Length	7.8 ps	
ε_x (90%, n)	8.249 mm-mrad	
ε_y (90%, n)	8.832 mm-mrad	
ε_z (90%, n)	55.223 keV-ps	

A 1.3 GHz CW solid-state power amplifier of 5 kW is to be used for the injector cavity so as to enable the ~1 mA electron beam reach 2.43 MeV.

An acceleration section to accelerate high brightness electron beam either in CW or pulsed mode is proposed to set after the injector. Two 9-cell superconducting cavities developed at DESY for the TESLA project and a 1.3 GHz, 30 kW CW mode klystron are to be used for this purpose. The main RF power coupler can only sustain 14 kW at the first stage, and the expected average beam current at about 30 MeV could be less than 1 mA. It will be upgraded later so that the beam current can be increased by 3-5 times. As such facility could offer a lot of research opportunities to related fields in PKU, so it is named as the Peking University Superconducting Accelerator Facility (PKU-SCAF). The layout of the facility is shown in Fig.10.

Table 5: Beam characteristics at the exit of one 9-cell cavity

E_{acc} MV/m	Phase degree	εx(90%,n) (cm-mrad)	εy(90%,n) (cm-mrad)	$\Delta E_k/E_k$ (%)	E_k (MeV)
25	20	0.8799	0.8116	0.24	24.912
20	20	0.7936	0.7408	0.29	20.402
15	20	0.7138	0.6693	0.40	15.552
10	20	0.6625	0.6275	0.53	11.383

For the Beijing Radioactive Nuclear Beam Facility (BRNBF), the niobium-sputtered copper QWR was the first choice as the energy boosting structure. Great efforts have been made in developing related facility and technology. A DC diode sputtering system was set up in 1997. The ultra-high vacuum chamber of the system is 0.6 m in diameter and 1.2 m in height. The base vacuum of the chamber can be pumped down to better than 10^{-7} Pa. A

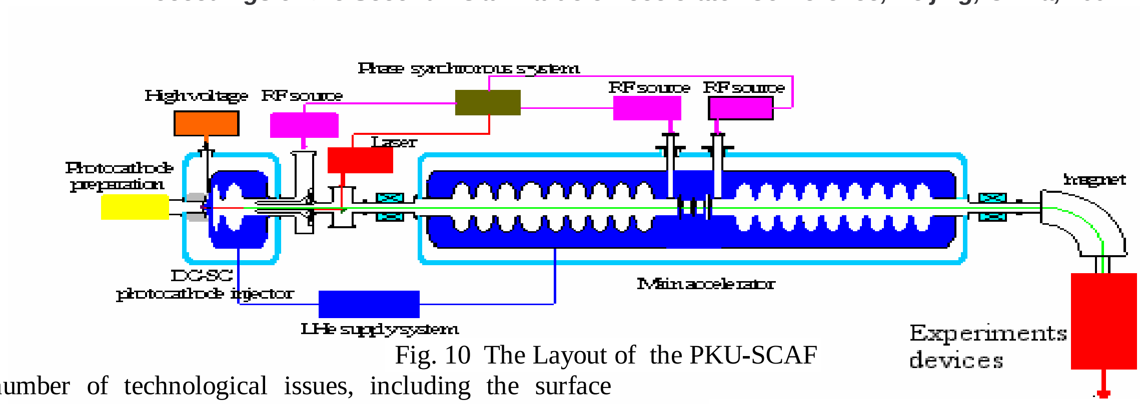

Fig. 10 The Layout of the PKU-SCAF

number of technological issues, including the surface cleaning of OFHC, Nb film uniformity, morphology and RF superconductivity and etc., have been developed on the system. Good film uniformity is difficult to obtain because of the complicated inner geometry of the QWR. To enable the niobium film adhered tightly to the surface of QWR, the OFHC QWR has to be treated with electro-polishing, high-pressure water rinsing, ethanol dehydrating and Ar ion cleaning in the vacuum. By adjusting the argon pressure, sputtering voltage and current, bias voltage and sputtering time good results were obtained [14], as can be seen in Fig. 11. The difference of thickness between inner and outer conductor of QWR is within 20%.

Fig.11 QWR before (left) and after niobium sputtering

Based on above-mentioned treatments, the manufacture of the first QWR with niobium coating was completed in October 1999. The Nb-Cu QWR was put into a specially designed cryostat to carry out various tests on its properties of RF superconductivity at 4.2K. The highest E_{acc} recorded in the test is ~ 6 MV/m. The QWR was then installed on the beam line of the EN Tandem for beam tests, where 6.8 MeV protons were used to simulate the medium β heavy ions (see Fig.12). The beam energy spectrum after the

Fig.12 The beam test of the Nb-Cu sputtered QWR

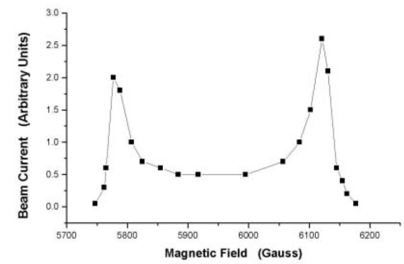

Fig.13 The energy spectrum after the QWR

QWR was measured by an analysing magnet, and the Eacc deduced from a stable operation is 3 MV/m with an RF input of ~6 W.(see Fig. 13)

4 CONCLUSION

The performance of the ISR-1000 shows that the ISR structure suits well for high average power RFQ in the sense of high RF efficiency and high working stability.

The feasibility of PKU-SCAF is reported; it is going to be constructed once it is fully funded. The Nb-Cu QWR will be jointly developed further by PKU and CIAE so that the first SC section after the HI Tandem will be available in the coming years.

REFERENCES

[1] I.M. Kapchinskij, V.A.Teplyakov, Prib.Tekh.Eksp., 1970, (4), P19
[2] A.Ratti, et al., Proc. EPAC 2000, P495
[3] H.V. Smith, et al., Proc. EPAC 2000, P969
[4] J.X. Fang, C. E. Chen et al., IEEE NS-32 (1985)2981
[5] Chen C.E., Fang J. X. et al., Proc. EPAC 1994, P2194
[6] J.X. Yu C. E. Chen et al., Trends in Nuclear Physics Vol.13, No.2(1996) 34
[7] C.E. Chen, J.X. Fang et al., Proc. EPAC 1996, P2702
[8] C.E. Chen, J.X. Fang et al., Proc. EPAC 2000, P1850
[9] Guan Xialing, et al., this conference
[10] C.E. Chen, K. Zhao, Proc. International Meeting on Frontiers of Physics, Oct. 1998, Malaysia, p.3
[11] K. Zhao, J. E. Chen et al, NIM A, 375(1996)147
[12] K. Zhao et al, NIM A 407(1998)322
[13] Guan Xialing, NIM A 382(1996) 241
[14] Jiankui Hao et a, Proc. PAC 2001, (to be published)
[15] Pan Oujia, Thesis, Peking University, 1992
[16] Zhang Honling, Thesis, Peking University, 2001
[17] Wang Zhenxia, Private communication, 2000
[18] D. Proch, Prog. Phys. 61(1998) 431-482
[19] K. Zhao, J. E. Chen et al, NIM A, 2001, (to be published)
[20] K. Zhao, J. E. Chen et al, NIM A 445 (2000) 394-398.