PERFORMANCE AND CONSTITUTION OF THE VACUUM SYSTEM IN THE JAERI AVF CYCLOTRON

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The JAERI AVF cyclotron system has been already constructed to promote the application of advanced radiation application. The pressure in the cyclotron vacuum chamber was designed mainly on the basis of the beam loss caused by interaction of accelerating ions with residual gas. An outline of the final system is described. Some results of evacuation curve measurement in the vacuum chamber and reliability tests for the vacuum gauge controller are also shown. In order to estimate the beam loss induced by residual gas in the cyclotron, the relationship between the intensity of accelerated ion beam and internal pressure was measured by gas feeding into the vacuum chamber.

1 Introduction

The JAERI AVF cyclotron[1,2] (K=110 MeV) system consists of two external ion sources, an ion injection line, a cyclotron and thirteen beam transport lines.

The vacuum system[3,4] was designed based on a plan as follows:

(1) Aluminum ducts, metal gaskets and all-metal gate valves were adopted to reduce outgassing from the vacuum components, because high transmission rate of ion beams is required mainly for heavy ion acceleration.

(2) Sputter ion pumps (SIP's) and cryogenic pumps (CRYO's) were chosen for simple composition and oil-free condition of the system. Magnetic suspended turbo molecular pumps (MSTMP's) were used for auxiliary evacuation.

(3) The vacuum system is controlled separately from cyclotron control, and operated in remote or local mode.

(4) Some parts of the vacuum controllers sensitive against radiation exposure were installed at the places where the radiation level is relatively low.

(5) Whole vacuum system is divided into 25 vacuum sections as shown in Fig. 1. Each section is managed independently and systematically.

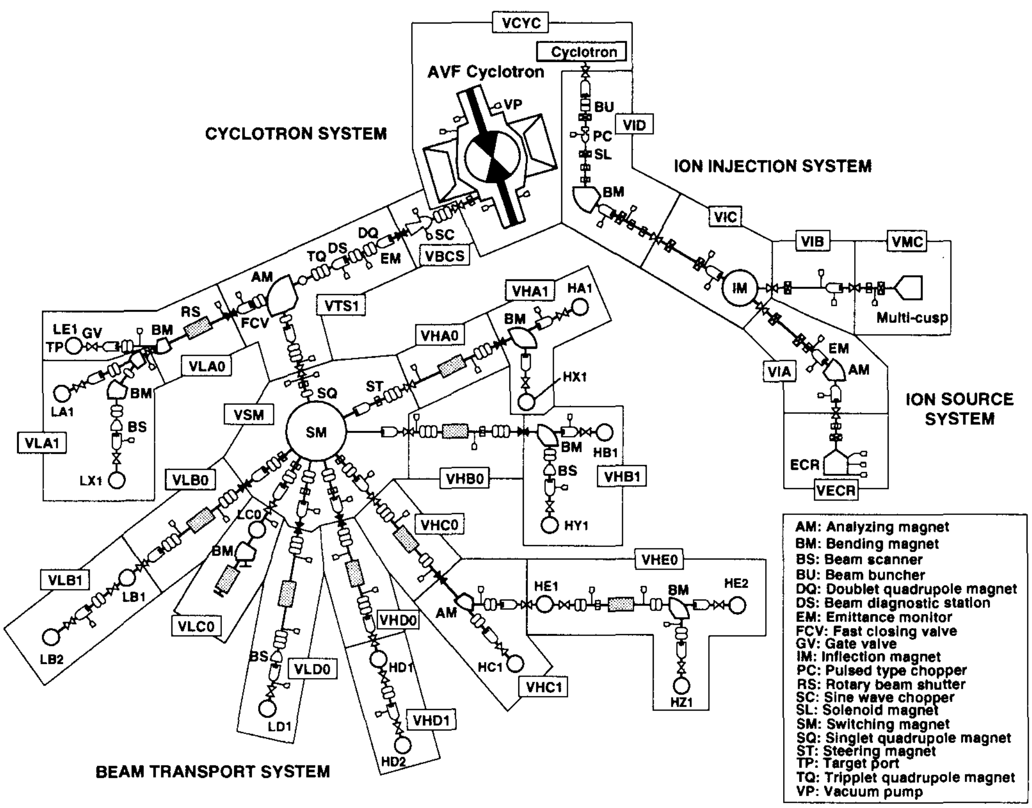

Fig. 1: General constitution and division of vacuum sections on the vacuum system for JAERI AVF cyclotron.

2 Pressure Required and Beam Transmission

Beam current loss depends on the total path length of the ion, the residual gas pressure and the cross section of charge exchange reaction with the gas, since the contribution of Coulomb scattering to the total beam current loss is generally much smaller than that of charge exchange reaction.

In the cyclotron, if the total number of turn is N, the total path length X is expressed by

$$X=\sum_{n=1}^{N} L_n = \frac{2\pi R_{ex}}{\sqrt{N}}\sum_{n=1}^{N}\sqrt{n} = 2\pi R_{ex}\left(\frac{2}{3}N+\frac{1}{2}\right), \qquad (1)$$

where R_{ex} is the extraction radius, L_n the traveling distance of accelerated ions at n-th turn. Since the average orbit radius is equal to about 2/3 of the extraction radius for large turn number.

For the maximum energy of 294 MeV for $^{84}Kr^{15+}$ in the JAERI AVF cyclotron, N is evaluated at 210 when the dee voltage of 33.5 kV is supplied under third harmonic mode, and X is calculated at 815 m where R_{ex} is 0.923 m. Assuming the pressure in the vacuum chamber is 6.7×10^{-5} Pa and the cross section of the charge exchange reaction[5], σ_T, is 9.1×10^{-17} cm^2, the transmission rate of $^{84}Kr^{15+}$ in the vacuum chamber, f_T, is estimated at 0.88 using the equation: $f_T = \exp(-2.47 \times 10^{14} \times P \times \sigma_T \times X)$, where P is the pressure of the residual gases (Pa).

The f_T for $^{84}Kr^{15+}$ in the ion injection system is evaluated at 0.93 for the beam-line length of 24 m, if σ_T[6] is assumed to be 1.7×10^{-14} cm^2 for 100 keV and the pressure of 6.7×10^{-6} Pa is required for the injection beam-line.

To estimate the beam transmission rate in the beam transport system, σ_T is written by the equation[7]:

$$\sigma_T = \sigma_L + \sigma_C = 9 \times 10^{-19} Q^{-0.4} \beta^{-2} + 3 \times 10^{-28} Q^{2.5} \beta^{-7}, \qquad (2)$$

where σ_L is the cross section of electron loss, σ_C that of electron capture, Q the charge state and β the velocity ratio of ion beam to light. For 322 MeV $^{129}Xe^{27+}$, the equation (2) gives 1.5×10^{-16} cm^2 where σ_L is 4.5×10^{-17} cm^2 and σ_C is 1.0×10^{-16} cm^2. The beam loss at 1.3×10^{-4} Pa is estimated at only 3 % for the longest beam-line of 54 m, and that for 2.5 MeV protons is similar to that for 322 MeV $^{129}Xe^{27+}$.

From the above results, the beam loss due to the interaction of ions with residual gases at the required pressure is considered to be less than 20 %, which is comparable to the beam losses by the acceleration and extraction processes for heavy ion beams.

3 Vacuum System

The main specifications of the vacuum system are shown in Table 1. Each vacuum section is partitioned off the gate valves so that the restoration work for vacuum failure can be localized. The cyclotron is protected from vacuum accidents by eight fast closing gate valves, which close within 16 msec, installed in several beam-lines.

Each vacuum section is also equipped with a wide-range vacuum gauge, at least, constituting of a pair of a Pirani and a cold-cathode gauge and also provides the leak lines for dry nitrogen gas and open air. Figure 2 illustrates the vacuum

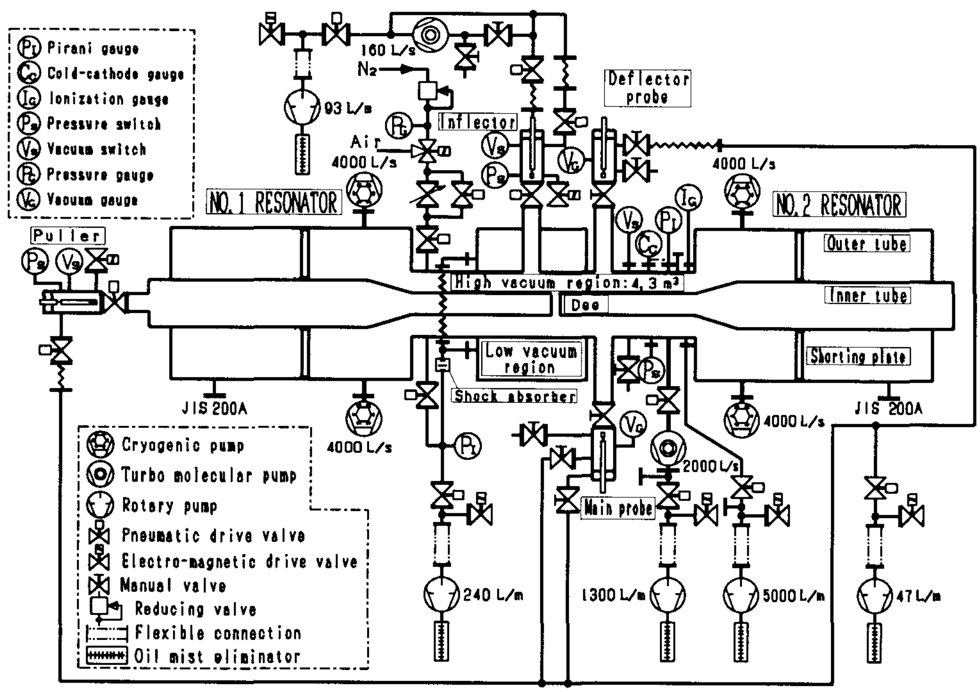

Fig. 2: Vacuum system of the JAERI AVF cyclotron.

system of the cyclotron. The main pumps are two pairs of CRYO's (4000 L/s), each pair is directly mounted at the bottom of each resonator, and a MSTMP (2000 L/s) is connected with the vacuum chamber. Differential evacuation systems are provided to easily exchange the inflector and puller electrodes, pull out the main and deflector probes without breakdown of high vacuum.

Table 1: Main specifications of the vacuum system.

Required pressure (Pa)	
Ion injection system	$6.7x10^{-6}$
Cyclotron and beam transport systems	$6.7x10^{-5}$
Number of pumps, valves and gauges	
Ion sputter pump	33
Cryogenic pump	10
Magnetic suspended turbo molecular pump	15
Rotary pump	22
Gate valve (more than 4 in.)	45
Gate valve (fast closing, 4 in.)	8
Right angle valve (4 in.)	45
Ionization gauge	4
Portable evacuation unit	8

In the ion injection line, the evacuation system consists of a CRYO (1600 L/s) and a MSTMP (270 L/s) installed at the beam diagnostic station. A thick beam-line duct 6 in. in diameter was selected for the ion injection to minimize the ion beam loss resulting from the large emittance of 400πmm ·mrad from the ECR ion source.

The beam-line duct 4 in. in diameter is made of aluminum alloy (A6063) to reduce outgassing and radioactivation in the beam transport line. Each vacuum section is roughly evacuated by a portable unit composing of a MSTMP and a rotary pump. High vacuum condition is held by some SIP's (60 L/s) in the section.

4 Measurement of Pumping Characteristics

An example of measured results of evacuation curve for the cyclotron vacuum chamber (VC) is shown in Fig. 3. The MSTMP line was opened at 17 min after rotary pump operation, followed by two-decades pressure drop, and then four CRYO's were started. The temperature of the CRYO's panel usually drops below 15 K after 90 min operation. In this example, the CRYO's operation stopped for 3.5 h because of a trouble of the vacuum gauge controller. However, the pressure reached about $1x10^{-4}$ Pa 20 h later, a steady state of the pressure around $1x10^{-5}$ Pa was achieved at 300 h through several cyclotron operations.

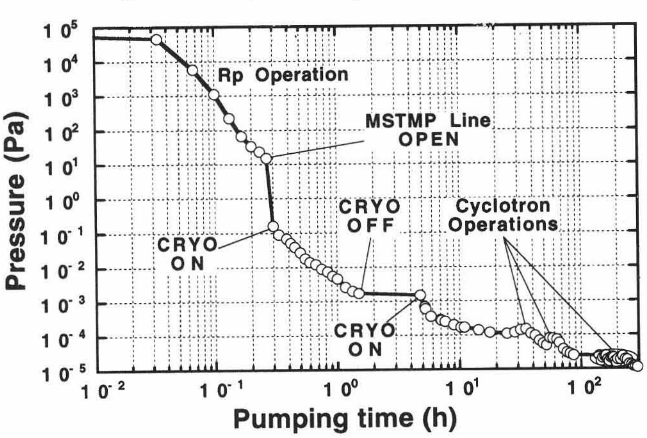

Fig. 3: An example of evacuation curve in VC.

5 Reliability of Vacuum Components

The cold-cathode gauges (CCG's) were introduced as the main vacuum gauge, which covers a wide range of pressure from 10^{-1} to 10^{-6} Pa. To examine the stability of the CCG, the pressure indication was compared with that of a typical ionization gauge at different pressures. The indication of the CCG increased about 15% relative to the ionization gauge for an operation time of 500 h at $5x10^{-2}$ Pa.

This suggests that the maintenance of the CCG is unnecessary for an operation time of $4x10^4$ h, assuming that the amount of dust deposited on the inner wall of the CCG are proportional to the operation time and the pressure, and also if a systematic error of 20 % is tolerable for the vacuum gauge.

We also examined the radiation resistance[8,9] of a wide-range vacuum controller (TPG300) equipped with radiation-sensitive semiconductor devices, such as CMOS-RAM's, by means of ^{60}Co γ-ray irradiation. The TPG300 was functionally disordered at an absorbed dose of 97 Gy (Si). Therefore, most of vacuum controllers were installed where the average dose-rate is low.

6 Beam Attenuation by Internal Gases

The beam loss in VC is almost proportional to the product of the pressure of residual gas, the cross section of collision and the traveling path of ion beam, and it may bring a critical problem in heavy ion acceleration. So, we try to examine the beam attenuation by controlling the pressure in VC.

A block diagram for the pressure control is shown in Fig. 4. The setting pressure in a gauge controller (MIG-921) is transmitted to a mass flow controller (CMS-201) through a pressure controller (CMS-101). The pressure in VC can be controlled finally by regulating the gas flow rate from a gas cylinder.

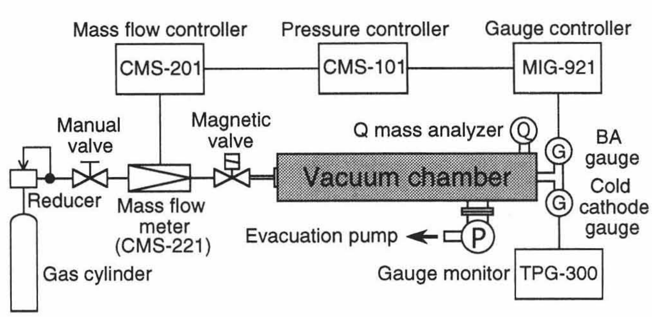

Fig. 4: A block diagram for pressure control in VC.

In order to measure the pressure distribution in VC, we replaced the head of a main probe with a vacuum gauge so that the radial distribution can be measured easily.

Figure 5 shows the pressure distribution along the radial direction as a function of gas flow rate. Though the pressure distributions of the cyclotron are roughly flattened independent of the gas flow rate, it appears somewhat higher at the central region.

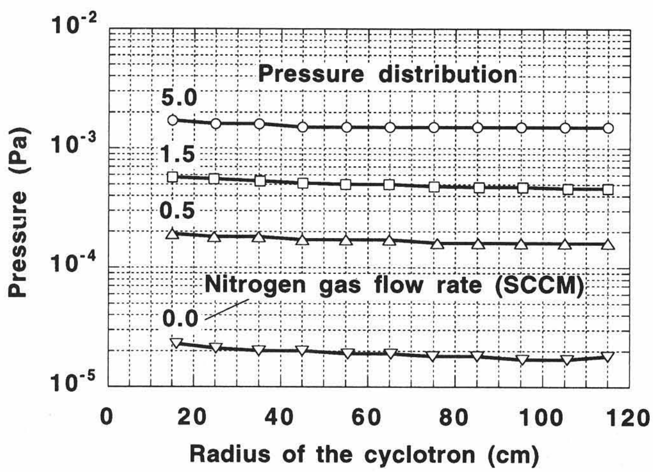

Fig. 5: Pressure distributions along the radius of the cyclotron.

We examined the attenuation of beam current by gas feeding into VC for 10 MeV H^+, 260 MeV $^{20}Ne^{7+}$ and 520 MeV $^{84}Kr^{20+}$.

Figure 6 shows that beam current along the radius of the cyclotron decreases with increase of the pressure in VC. The beam attenuation in a perpendicular injection hole to the cyclotron was 0.71 for the pressure increase from $4.2x10^{-5}$ Pa to $3.5x10^{-3}$ Pa.

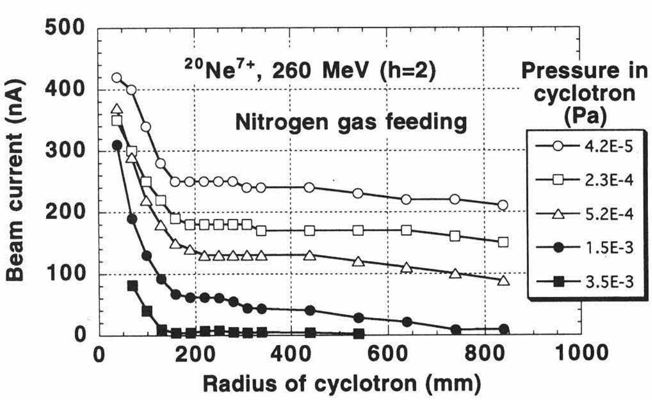

Fig. 6: Beam current attenuation of 260 MeV $^{20}Ne^{7+}$ ions along the radius of the cyclotron.

The tendency of beam attenuation for 520 MeV $^{84}Kr^{20+}$ ions is approximately similar to 260 MeV $^{20}Ne^{7+}$ ions. The pressure dependence on the attenuation rate as shown in Fig. 7 becomes obviously to be large according to the radius of the cyclotron.

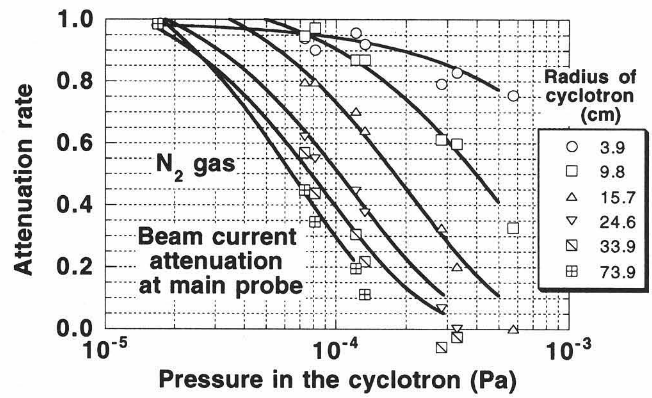

Fig. 7: Pressure dependence on attenuation rate of 520 MeV $^{84}Kr^{20+}$ ions.

However, 10 MeV H^+ ions, are lost about 17 % themselves only in the injection hole, have no attenuation in the acceleration region of VC over the pressure range of $2.0x10^{-5}$ Pa to $1.7x10^{-3}$ Pa by nitrogen gas feeding.

7 Present Status

The vacuum system of the JAERI AVF cyclotron has been operated since the start of evacuation in October 1990. We had a few typical troubles as follows: 1) aluminum blades of a MSTMP (600 L/s) in the beam transport line were destroyed and the fine broken pieces were diffused into it, 2) the leakage of compressed air into the No. 2 resonator occurred at the copper pipe joint of the contact finger, 3) the leakage of open air also happened at the X-ring of the No. 2 phase slit.

At present, the pressure in VC sometimes lowers about $8x10^{-6}$ Pa at steady state without accelerating of ion beam.

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