VACUUM SYSTEM OF THE JAERI AVF CYCLOTRON

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Abstract

The JAERI AVF cyclotron with external ion sources was installed[1] at JAERI Takasaki to promote the research of advanced radiation application. It was designed to accelerate various kinds of ions from proton to xenon in a wide range of energies. An outline of the vacuum system of the cyclotron is described.

Introduction

The JAERI AVF cyclotron (K=110 MeV) consists of two external ion sources, an ion injection system, a cyclotron system and a beam transport system. The cyclotron is of the same model 930 of Sumitomo Heavy Industries, basically the same model as that of the National Institute of Radiological Science. An emphasis is put on acceleration of various heavy ions from an ECR ion source (OCTOPUS). The beam transport system consists of eight main horizontal beam courses with two horizontal and four vertical branch courses.

The vacuum system has been 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 good transmission rate of ion beam is required mainly for heavy ion acceleration.

(2) Sputter ion pumps (IP) and cryogenic pumps (CRYO) were chosen to make simple composition and oil-free condition. Magnetic suspended turbo molecular pumps (MSTMP) were also selected for auxiliary evacuation.

(3) The vacuum system can be controlled separately from cyclotron control, and operated in different modes of remote and local controls.

(4) Some parts of the vacuum controllers which are sensitive against radiation exposure were installed where the average dose-rate as a contribution of secondary radiation is relatively low.

(5) Whole vacuum system is divided into 26 vacuum sections. Each section are managed separately and systematically.

This paper describes vacuum pressure required relative to beam transmission, construction of the vacuum system and considerations on vacuum components.

Pressure Required and Beam Transmission

Beam current loss in the vacuum chamber is determined by the vacuum pressure, the total ion path length, and the cross section of charge exchange reaction with residual gas, since the contribution of Coulomb scattering to the total beam current loss is smaller in the cyclotron orbit by three orders than that of charge exchange reaction of $^{84}Kr^{15+}$ for 180 keV.[2]

When the traveling distance at n-th turn of accelerated ions is L_n, the total path length X is expressed by

$$X = \sum_{n=1}^{N} L_n = \frac{2\pi R_{ex}}{N^{0.5}} \left(\sum_{n=1}^{N} n^{0.5} \right), \qquad (1)$$

where N is the total number of turn and R_{ex} is the extraction radius. And, X can be calculated simply by

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

since the average orbit radius is equal to about 2/3 of the extraction radius for a large turn number.

The number of turn N of accelerated ions is written by

$$N = \frac{K}{4eV_D \sin(h\theta/2) \sin(\phi_0 + h\theta/2)} \cdot \frac{Q}{M}, \qquad (3)$$

where K is the K-number of the cyclotron, Q the charge state, e unit charge, V_D (MV) the dee voltage, h the harmonic number, θ the span angle of the dee, ϕ_0 the acceleration phase and M the mass number.

For the maximum energy (295 MeV) of $^{84}Kr^{15+}$ in the JAERI AVF cyclotron, N is evaluated at 210 for h=3 and $V_D=33.5\times10^{-3}$, and X is calculated at 815 m for $R_{ex}=0.923$ m. Assuming the pressure required for the vacuum chamber is 6.7×10^{-5} Pa (5×10^{-7} Torr) and the cross section of the charge exchange[2] is 9.1×10^{-17} cm^2, the transmission rate of $^{84}Kr^{15+}$ in the vacuum chamber is estimated at 0.88 by using the equation: $f_T=\exp(-2.47\times10^{14} \cdot P \cdot \sigma_T \cdot X)$, where σ_T (cm^2) is the cross section of charge exchange reaction and P (Pa) is the pressure of the residual gas.

The transmission rate of $^{84}Kr^{15+}$ in the ion injection system is evaluated at 0.93 for the beam-line of 24 m, assuming that σ_T[3] is 1.7×10^{-14} cm^2, which is given for 100 keV, and the pressure of 6.7×10^{-6} Pa (5×10^{-8} Torr) 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[4]:

$$\sigma_T = \sigma_L + \sigma_C = 9\times10^{-19} Q^{-0.4} \beta^{-2} + 3\times10^{-28} Q^{2.5} \beta^{-7}, \qquad (4)$$

where σ_L is the contribution of electron loss, σ_C that of electron capture and β the velocity ratio of ion beam to light. For 310 MeV $^{129}Xe^{27+}$, the equation (4) gives 1.7×10^{-16} cm^2 where σ_L is 4.6×10^{-17} cm^2 and σ_C is 1.2×10^{-16} cm^2.

The beam current loss at 1.3×10^{-4} Pa is estimated at only 3 % for the longest beam-line of 54 m, and the loss for 2.5 MeV protons is the same order of that for 310 MeV $^{129}Xe^{27+}$.

From the above results, It is expected that the beam current loss due to the interaction of ion beams with residual gas at the pressure required is quite small compared with that due to other contributions to the loss in the whole cyclotron system.

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 installed in several beam-lines, which work within 16 msec.

Table 1
Main specifications of vacuum system

Pressure required (Pa)	
Ion injection system	6.7×10^{-6}
Cyclotron and beam transport systems	6.7×10^{-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	2

Fig. 1 illustrates the vacuum system of the cyclotron. The main pumps are four CRYO's (4000 L/s), each pair of them is directly mounted on 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.

In the ion injection system, the evacuation system, as shown in Fig. 2, consists of CRYO (1600 L/s) and MSTMP (270 L/s), which were installed at the beam diagnostic station. A thick beam-line duct of 6 in. in diameter was selected for the ion injection to minimize the ion beam loss resulting from the large emittance of 400πm m · mrad from the ECR ion source.

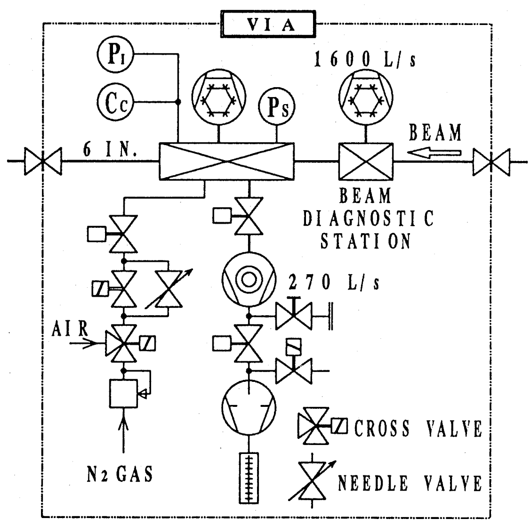

Fig.2 Construction of a vacuum section in the ion injection system

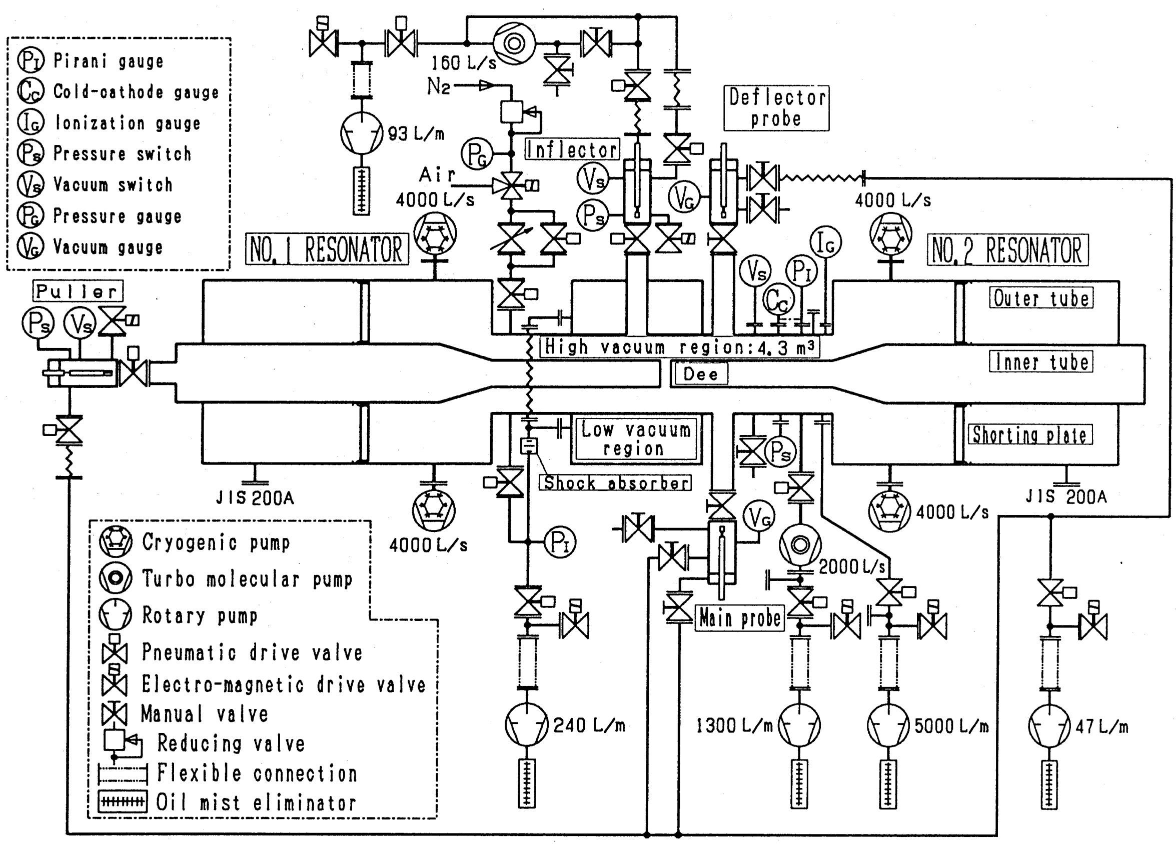

Fig. 1 Vacuum system of the JAERI AVF cyclotron

An example of vacuum sections in the beam transport system after extraction from the cyclotron is shown in Fig. 3. The beam-line duct of 4 in. in diameter is made of aluminum alloy (A6063) to reduce outgassing and radioactivation. Each vacuum section is roughly evacuated by a portable unit consisting of a MSTMP and a rotary pump. High vacuum condition is held by two IP's (60 L/s) in the section.

A rotary pump was also installed to exclusively evacuate the narrow space where an axial seal is used around the driving shaft of a rotary beam shutter, inserted in a penetration beam-line duct across the radiation shielding wall.

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

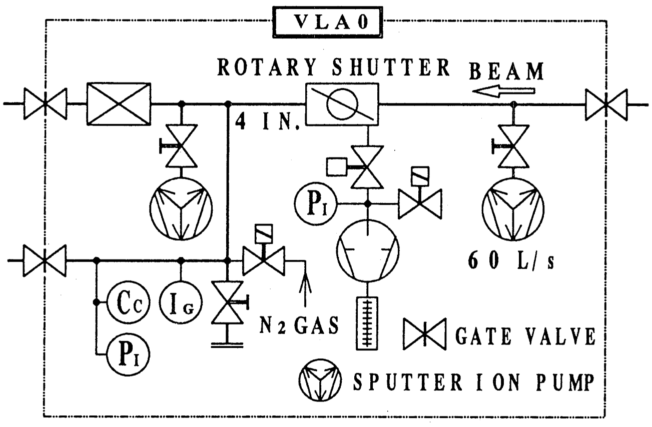

Fig. 3 Construction of a vacuum section in the beam transport system

The pressure distribution is estimated by calculation based on the outgassing rate[5] from component materials and geometrical structures. Figure 4 shows the calculated pressure distribution in the cyclotron. The total outgassing load was evaluated at $1.6\text{x}10^{-5}$ Pa · m^3/s, and the pressure was estimated at $2.8\text{x}10^{-5}$ Pa at the top of the dee, and $7.3\text{x}10^{-5}$ Pa at the bottom in the perpendicular injection hole.

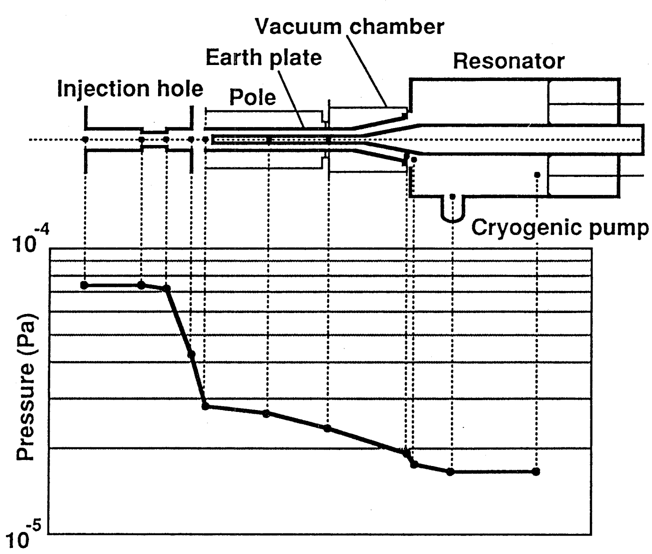

Fig. 4 Pressure distribution in the JAERI AVF cyclotron

The calculated pressures satisfy both designed values of $3.3\text{x}10^{-5}$ Pa for the cyclotron and the beam transport system, and $3.3\text{x}10^{-6}$ Pa for the ion injection system with the exception of the small space of the above injection hole.

Considerations on Vacuum Components

The cold-cathode gauges (CCG) were introduced as the main vacuum gauge for the JAERI AVF cyclotron, which can cover a wide range of pressure from 10^{-1} to 10^{-6} Pa. In order to examine the stability of the CCG, an improved Penning gauge, the pressure indication was compared with that of a typical ionization gauge at different pressures. The indication of the CCG increased by about 15% relative to the ionization gauge for the operation time of 500 h at $5\text{x}10^{-2}$ Pa.

This suggests that the maintenance of the CCG is unnecessary for an operation time of $4\text{x}10^4$ 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 the deviation of 20 % is tolerable for the vacuum gauge.

We also examined the radiation resistance[6-7] of a wide-range vacuum controller (TPG300) equipped with radiation-sensitive semiconductor devices, such as CMOS-RAM's, by using ^{60}Co γ-ray irradiation. The TPG300 was functionally disordered at an absorbed dose within 100 Gy (Si). Therefore, most of vacuum controllers were installed where the average dose-rate is low. However, some of them were set around the upper beam-line for unavoidable reasons.

Present Status

There has been no serious trouble in the vacuum system since the start of evacuation in October, 1990. After a year passed, the pressure is $2\text{-}3\text{x}10^{-6}$ Pa in the ion injection system, $3\text{-}5\text{x}10^{-5}$ Pa in the vacuum chamber of the cyclotron, for better condition, and $4\text{-}60\text{x}10^{-6}$ Pa in most of beam transport system.

The vacuum condition of the cyclotron system is going up to a steady state gradually, and the pressure required will be also satisfied in whole vacuum sections in near future.

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