CONSIDERATION OF HIRFL VACUUM PRESSURE

Wang Yifang, Tang Jingyu and Lei Wei

Institute of Modern Physics
Chinese Academy of Sciences
National Laboratory of Heavy Ion Accelerator
Lanzhou, 730000, China

In the paper, according to the existing problems of HIRFL in vacuum, some researches were made carefully in which, the processes of the ion beams hitting the residual gas in vacuum chamber are described. The results by the theoretical computation indicate that the pressure for the injector SFC and its injection line must be better than 5×10^{-6} Pa and for the main cyclotron SSC as well as the beam transport lines must be better than 1×10^{-5} Pa at least. So in our case, the construction of a new vacuum chamber for SFC is needed.

1. Outline

The Heavy Ion Research Facility in Lanzhou (HIRFL) is a cyclotron complex, which consists of an ECR ion source, a short beam line between ECR and SFC, an injector SFC (Sector Focusing Cyclotron), a pre-beam line, a main cyclotron SSC (Seperated Sector Cycloton), a post-beam line and 8 experimental devices included RIBLL as well as a bypass beam line used to transport low energy beam from SFC to the experimenal devices directly (Fig.1).

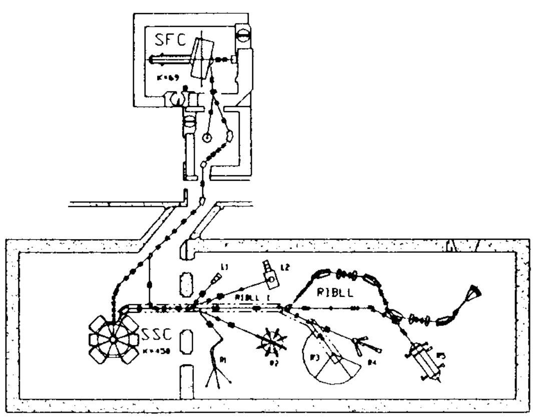

Fig.1 The layout of HIRFL

The injector SFC was converted from an existing classcal cyclotron in 1986. In the begining of operation of this machine, a PIG ion source located in the center of SFC was used to afford some light heavy ion beams. Because the PIG ion source as an inner source is a gas source itself. So the working vacuum pressure of SFC was only $1\sim2\times10^{-4}$ Pa in that time. When some light heavy ion beams such as Carbon, Nitrogen and Oxigen with higher energy were accelerated in SFC, the beam losses were not very serious. But for the heavier ion beams whose atomic weight are larger than 40, such as Argon, Kripton, Xenon, etc, the beam transparencies were decreased obviously.

2. Some Theoretical Researches

As we well know, when the different kinds of charged particles with different energies are moved and accelerated in a vacuum chamber, part of them will be hit with the residual gas and lost over. The loss probability depends on the vacuum pressure in the vacuum chamber, the kind of the charged particles, their energies, etc. Considering the case of HIRFL, the species of the accelerated particles from Carbon to Xenon, even to Uranium in futher, the energy range from 1.0KeV/u to 100MeV/u, so the various hitting processes should be considered to obtain the reasonable reguirements for the different cyclotron and beam line, especially for the injector SFC.

In the considered energy range, the hitting of the heavy ion beams with the residual gas includes the following processes mainly: electron capture, electron loss, anglar scattering and gas ionization.

2.1 Electron capture process

In genaral case, only when the charged states of the incident ions are higher than the equilibrium charged state, the electron capture process has the larger hitting cross section. In fact, the capture process means that one incident ion particle with a deeper potential trap captures the electrons with a shallower trap in target molecules. It is imaged that the bigger is the vilocity v of the incident particles, the smaller is the probability. When v is small enough, $mv^2/2<U$ (U is the capture potential

trap), the reaction cross section will be saturated. According to an amount of the experimental data[1-5]. Especially for the experimental data of ions with higher charged states and higher energies, we have obtained several experience fitting formulas. The experimental results show when the energies of ions are very low *($v \le v_0$, $v_0 = e^2/h = 2.188 \times 10^6$ m/s)*, the capture cross section independs on the target gas and the velocities of incident ions roughly. From the experimental data shown in Fig.2, the following approximate formulas are obtained:

$$\sigma_e(q) = 0.93 \times 10^{-15}(q-1),$$
$$(v/v_0 \le 0.5, \, in \, H_2 \; and \; N_2)$$

the capture cross sections decrease rapidly, when v increases. The cross section in the heavy target gas is much larger than that in H_2 and proportional to q^2 (see Fig.3a and 3b). They are described by formulas as follows respectively:

$$s_c(q,v) = 6 \times 10^{-15} \frac{q^2}{50 + (v/v_0)^7},$$
$$(0.5 \le v/v_0 \le 7, \, in \, H_2)$$

$$s_c(q,v) = 3 \times 10^{-15} \frac{q^2}{75 + (v/v_0)^{4.6}},$$
$$(0.5 \le v/v_0 \le 25, \, in \, N_2)$$

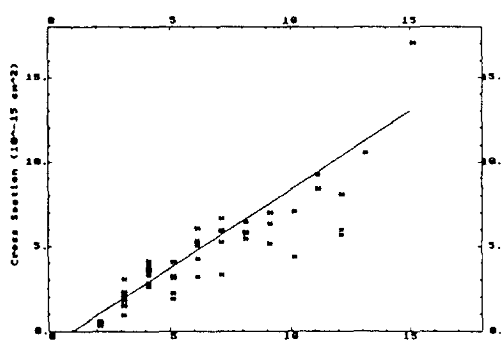

Fig. 2 The relation between the cross section of electron capture and the charged state
(target: H_2 and N_2, $v/v_0 \le 0.5$)

2.2 The electron loss process

The more successful method which describes the electron loss process is DZT method[6] in which, the values of ionizated energies of different shell in various atoms are needed. It is very completed although the results are conformed to the experimental ones. The experience formulas are obtained according to the amount of experimental data[1-5] (Fig. 4):

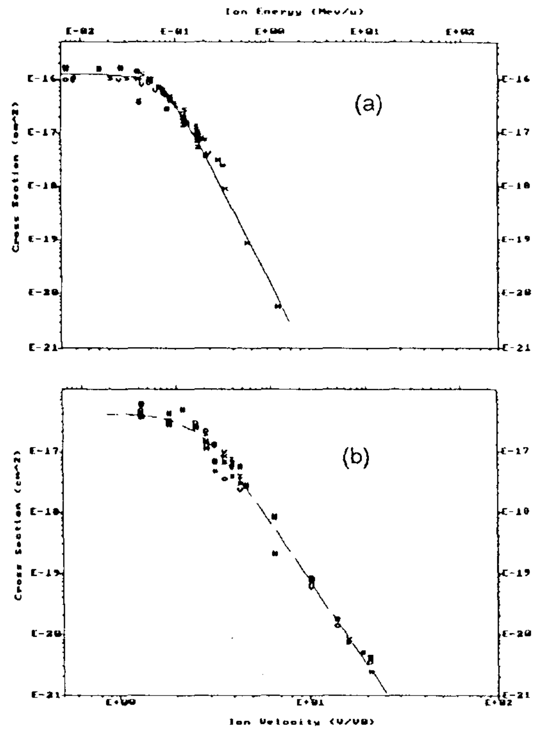

Fig. 3 The relation between the cross section of the electron capture and the ion velocity(energy)
(a) Target H_2, σ/q^2, $0.5 \le v/v_0 \le 7$
(b) Target N_2, σ/q^2, $0.5 \le v/v_0 \le 25$

$$\sigma_1(q,v) = 1.5 \times 10^{-15} q^{-1.8} (v/v_0)^2,$$
$$(cm^2, v/v_0 \le 5, \, in \, N_2)$$

$$\sigma_1(q,v) = 1.5 \times 10^{-17} Z_i^3 q^{-2} (v/v_0)^{-2},$$
$$(cm^2, 5 \le v/v_0 \le 25, \, in \, N_2)$$

When the velocity of the incident ions $v < u$, where u is the obit velocity of electrons to be lost, the loss cross section of the electrons increases along with v increasing. While $v > u$, the section decreases along with v increasing. So there is a maximum of the loss cross section of electrons near u.

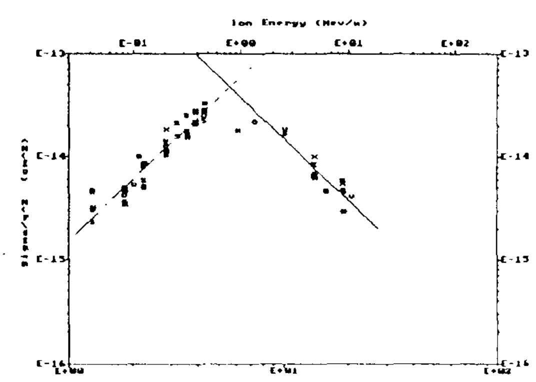

Fig. 4 The relation between the cross section of the electron loss and ion velocity(energy)
(Target: N_2, a: $\sigma \times q^{1.8}$, $v/v_0 \le 5$; b: $\sigma \times q^2/Z^3$, $5 \le v/v_0 \le 25$)

2.3 The equilibrium charged state

When Ions hit the target atoms, the processes of electron capture and electron loss happen simutaneously. When the cross section of electron capture is larger than that of electron loss, the charged states will be decreased, and conversely, the charged states will be increased. If there exist enough chances to hit each other, the ion beams will reach a state of equilibrium charged distribution in which the cross section of electron capture equals that of electron loss roughly. The definition of the equilibrium charged state is as follows:

$$\bar{q} = \sum_q qF(q)$$

where $F(q)$ is the distribution function of charged state. The equilibrium charged state independs on the initial charged states. It is the function of the velocity of ions and atomic number of target atoms in thin gas, in which the equilibrium charged state may be indicated as follows[7] :

$$\bar{q} / Z = 1 - C\exp(-v/(v_0 Z^{\gamma})), \quad (v/v_0 \geq 1)$$

For the more correct description, coefficients C and γ are different for the various kind of ions and targets. but for $C=1$ and $\gamma=2/3$, the results are good enough to describe the experiments. For the targets of the solid state, there is a density effect[8],

$$\bar{q} / Z = (1 + (Z^{-a} v / v')^{-1/k})^{-k},$$

$$(Z \geq 16, \quad v/v_0 \geq 1, \quad v' = 3.6\times 10^8 cm/s,$$

$$a = 0.45, \quad k = 0.6)$$

Due to the contribution of multi-electron loss process, the distribution of the equilibrium charged state is unsymmetrical. There is a longer tail in the side of high charged state. We still describe it using Gaussian-like distribution. The width function d of distribution is

$$d = (\sum_{q'} (q' - \bar{q})^2 F(q'))^{1/2} = d_0 \left\{ \bar{q}(1 - (\bar{q}/Z)^{1/k} \right\}^{1/2}$$

where d_0=0.5, k=0.6.

3. The transparency of beam transportation in HIRFL vacuum chamber

3.1 The computation method of the transparency of beam transportation in vacuum chamber

According to the concept of cross section, the loss rate of which the beam pass through the medium of thickness ds is expressed as

$$dI / I = N\sigma(E)ds$$

where I is the beam intensity, N is the molecular number of the residual gas in unit volume in vacuum, $\sigma(E)$ is the total cross section of charged exchange related to the energy $(\sigma(E) = \sigma_c + \sigma_l)$. The expression of the transparency of beam transportation in vacuum is obtained by integration of above expression:

$$\eta = \frac{I}{I_0} = e^{-\int N\sigma(E)ds}$$

N can be expressed by vacuum pressure P. If P is expressed in unit 10^{-6} Pa, and using $G(E)$ (unit 10^{-15} cm^2) instead of $\sigma(E)$, so that

$$\eta = e^{-0.472\int \bar{P}G(E)ds}$$

where the unit of s is meter. In the transport line, E = constant, so

$$\eta = e^{-0.472\bar{P}G(E)s}$$

In accelerator, E will be increased. When we know the relation between G and E, it is very easy to obtain thr transparency. In cyclotron, the energy is changed in each turn jumpily, the transparency can be expressed as

$$\eta = e^{-0.472\sum_{i=1}^{2N} PG(E_i)\pi R_i}$$

In the expression N is the number of the accelerated turn and beams are accelerated twice for each turn, Ri is the radius of averagy trajectory after the ith accelerating. The beam transparencies in transport line and cyclotron can be obtained by using this expression and the fomulas of the charged exchange cross section mentioned above. By the way, the effect of the gas compositon in vacuum must be considered. According to the measurement and analysis, when the vacuum pressure is lower than 1×10^{-5} Pa, the content of H_2 is about 40%, the content of the heavier gasses, such as CO, N_2, H_2O, Ar and so on, is about 60%. So N_2 is considered as the main composition approximately. When the pressure is going better, the ratio of H_2 composition increases, for example,when 1×10^{-8} Pa, H2 is about 85%, N_2 is only 15%. In the case, two compositions must be considered.

3.2 The computation results for the vacuum requirements of HIRFL

According to the energies and the charged states of accelerated ions in the various parts of HIRFL, such as the vetical injtion line between ECR source and SFC, injector SFC, pre-beam line between two cyclotrons , main cyclotron

SSC, post-beam line and so on, the relations between beam transparency and the vacuum pressure are computed respectively (Fig. 5). From these curves, we can find that the vacuum pressures in injector SFC and the corresponding vetical injection line should be better than that in SSC if we keep the same transparency. We hope the vacuum pressure in SFC and its injection beam line both should be 5×10^{-6} Pa and in the SSC and the rest beam lines should be 1×10^{-5} Pa at least to keep the higher transparency efficiencies for various heavy ion particles.

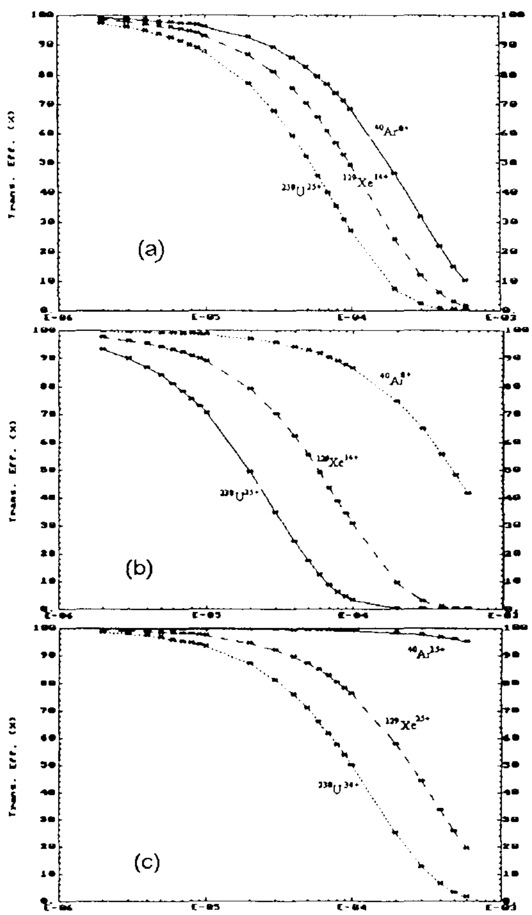

Fig.5 The beam transparencies in the vacuum of HIRFL
(a) The injection beam line of SFC: Ar-2.7 KeV/u, Xe-1.0 KeV/u, U-1.0 KeV/u
(b) SFC: Ar-2.35 MeV/u, Xe-0.77 MeV/u, U-0.7 MeV/u
(c) SSC: Ar-25 MeV/u, Xe-8.0 MeV/u, U-7.37 MeV/u

4. Conclusion and discussion

By the researches of the heavy ion beams with different energies hitting the residual gasses in vacuum, the quantitative computation of the beam losses in the various sub-systems of HIRFL has been done. The results indicate that the requirements in SFC and corresponding vetical injection beam line are higher than that in SSC and the rest beam line. In SFC and the vertical beam line, the vacuum pressure should be better than 5×10^{-6} Pa and in SSC and the other beam line it should be better than 1×10^{-5} Pa respectively.

In the present case of HIRFL, the requirements of the vacuum pressure in all of the sub-systems are almost satisfied except SFC, which we mentioned in outline above. We have tried to improve the vacuum pressure up to 5×10^{-5} Pa. And it is very difficulty to get higher pressure because of the existing intrinsic defects both in the structure and manufacture. So just now we plan to build a new vacuum chamber of SFC, in which the mono-structure of two layers and so on will be considered.

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