PROGRESS ON SPACE CHARGE COMPENSATION STUDY IN LOW ENERGY HIGH INTENSITY H^+ BEAM*

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Abstract

This article lays emphasis on the relationship between the Space Charge Compensation (SCC) and the beam quality in different conditions. Ar and Kr are used to compensate a 35keV/90mA H^+ beam with the gas pressure from 3.7×10^{-4} Pa to 6×10^{-3} Pa. We measured the energy spectra of Extra Compensation Gas Ions (ECGI), the beam profiles and the emittance variation. After that the potential and the rest charge distributions in the beam are calculated by analyzing the ECGI energy spectra and beam profiles, aiming to seek out the best circumstance for SCC dominated low energy high intensity ion beams.

INTRODUCTION

Spontaneous space charge compensation occurs in all accelerator systems. It is an effective focus means to suppress the beam divergence as well as the emittance increase[1]. Compared to focusing facilities, SCC is much easier to realize and have a wider range nearly all over the beam, although it is sensitive to electromagnetic fields[2]. Moreover, the control of emittance is practical by means of SCC[3].

The SCC with extra Ar injection was preliminarily studied at the pressure from 1.5×10^{-3} Pa to 1.6×10^{-2} Pa[4]. ECGI energy spectra were carefully investigated and it was found that the best compensation occurs at the pressure of 4×10^{-3} Pa. Higher than that the SCC showed no better performance but the beam lost was serious. However, this study is very limited because the insufficient conditions on the test bench. Precise study of SCC requires the ECGI energy spectra and compensated beam profiles on the same section, but on our test bench there is a 360mm distance between the beam profile measurement facility and the energy spectrometer. And for some reasons, we did not measure the beam emittance at that time. Additionally, only Ar was used as the compensation gas with the limited background vacuum of 1.5×10^{-3} Pa, which dramatically confined the pressure range in the study.

In order to understand better on the SCC effect, several improvements have been done to upgrade the conditions for the SCC research. And we will present and analyze the measurement results of the beam profile, the ECGI energy spectrum and the beam emittance. At the end of this article, from all these results and analysis, the influences of the SCC effect to the beam quality are summarized.

*Work supported by National Science Fundation of China. 11075008, and State Key Laboratory of Nuclear Physics and Technology.
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TEST BENCH

The scheme of the improved test bench is shown in Fig. 1. The original test bench[5] mainly consists of a compact 2.45 GHz Permanent Magnet Electron Cyclotron Resonance (PMECR) ion source[6], a Semi-closed solenoid[7], an SCC drift section, an emittance meter, three Faraday Cups (FC) and two turbopumps. Improvements have been made on the SCC drift section recently to offer more precise experimental conditions. A newly designed beam profile meter is specifically installed on the same section to the beam spectrometer. Besides, to improve the vacuum a third turbopump is added and a water-cooled difference suction is inserted between the solenoid and the SCC drift section. The difference suction obstructs gas from ion source, and lower temperature leads to less gas release. These measures improved the background vacuum from 1.5×10^{-3} Pa down to 3.7×10^{-4} Pa.

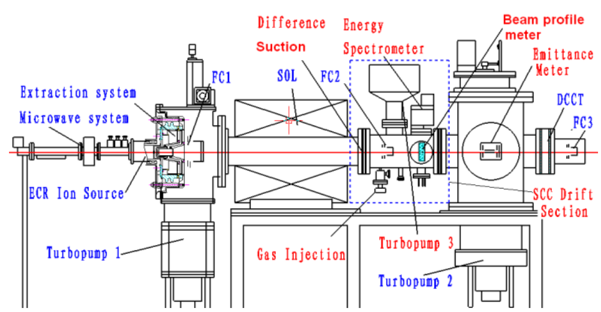

Figure 1: Scheme of the test bench, read calligraphy indicates the facilities specially for the SCC study.

The ion source generates a 35keV/90mA H+ beam. The beam focus can be controlled by the solenoid. Compensation gas is injected in the front of the drift section After a SCC distance of 285 mm, the ECGI energy spectra and beam profiles can be measured. The emittance measurement section is 360 mm after the beam profile and energy spectrum measurement position.

EXPERIMENTAL RESULTS

ECGI Energy Spectrum

The energy of the ECGIs shows the beam potential, and the amount of ECGIs equals the amount of electrons compensating the beam. So the measurement of ECGI energy spectra is an effective method to study the SCC effect without interrupting it. Three sets of ECGI energy spectra are measured in three situations: a converging beam compensated by Ar, a converging beam and a diverging beam compensated by Kr, respectively.

The ECGI energy spectrum intensity *Ig* is deemed as a function of beam radius *r*, beam ion density *n(r)* and beam potential *ϕ(r)* [4]

$$Ig = C\, r\, n(r)\, \phi(r)^{0.5} \quad (1)$$

where *C* is a constant. Fig.2(a) shows a typical energy spectrum in Kr SCC at the pressure of 3×10^{-3} Pa. The peak point of this curve indicates the generation rate of electrons by the compensation gas. And the right cut-off point of $Ig = 0$ on the X axis indicates the Potential in Beam Center (PBC). The relation of spectrum peak and PBC *vs.* vacuum are shown in Figure 2 (b) and (c).

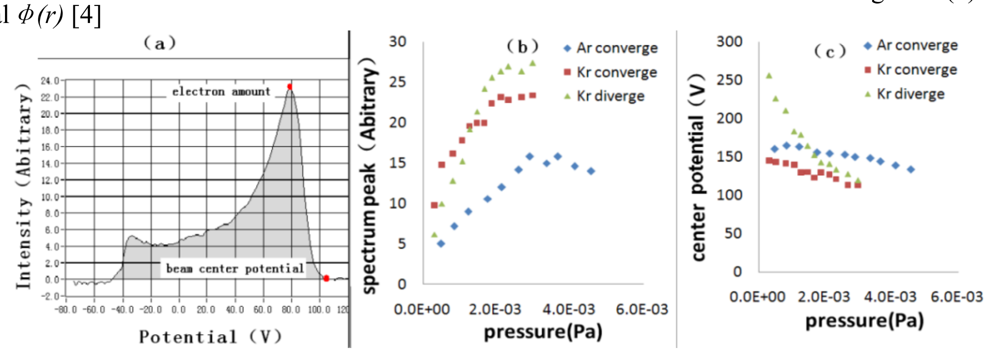

Figure 2: (a)Typical energy spectrum. (b)Energy spectrum peak in different conditions. (c) Beam center potential indifferent conditions.

Fig. 2(b) reveals that more extra gas injection generates more electrons and basically the rising is linear. However, the rising stops if the pressure is too high, and the electron amount tends to be saturated. For Ar compensation, the saturating point is about 3×10^{-3}Pa, and for Kr it is about 2×10^{-3}Pa. Fig. 2(b) also illustrates that Kr generates more electrons than Ar at any same pressure. And the electron amount is more sensitive to the extra gas amount in diverging beams than in converging beams.

Fig. 2(c) shows an inclination that the PBC decreases with the rising extra gas injection. Similar to Fig. 2(b), Kr compensates the PBC more efficiently, and the effect of SCC is more significant in diverging beams.

Beam Profile

The beam profile measurement is the most visualized and effective way to observe the beam quality. Fig. 3 shows a diverging H^+ beam is measured with the increasing extra gas injection. It is found that the beam gets piled to the center. The beam profiles show little improvement when the pressure is higher than 2.1×10^{-3} Pa for Kr and 2.9×10^{-3} Pa for Ar.

Another observation is unpleasant that along with the increase of the extra gas injection, the beam radius extends from 18 mm to 22 mm. This phenomenon implied that the extra compensation gas may deteriorate the beam quality.

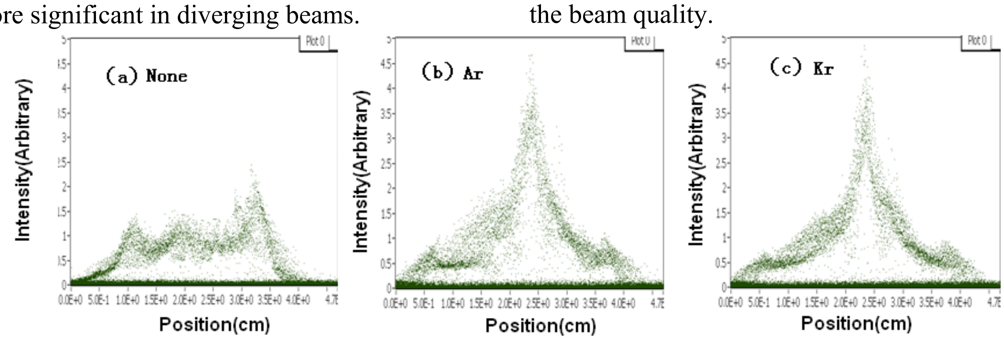

Figure 3: beam profile variation in SCC effect. (a)no extra gas added. (b)Ar as compensation gas, pressure is 2.9×10^{-3} Pa. (c)Kr as compensation gas, pressure is 2.1×10^{-3} Pa.

Emittance Variation

Beam emittance contains divergence information that cannot be obtained in the ECGI energy spectra and beam profiles. So emittance measurement is performed in Ar and Kr compensation and results are delineated in Fig. 4. The beam emittance without extra gas is set as 100% to calibrate the Y coordinate. As the PBC declines and the beam distribution converges to the center with the extra gas compensation, a reduction of beam emittance can be expected. However, the emittance rises again at about 4.5×10^{-3} Pa for both Ar and Kr. Furthermore, the trend lines show that basically Ar is better than Kr in controlling beam emittance. These two results suggest that the scattering effect in the beam conflicts with the SCC and even becomes the main effect at high pressure, as heavier molecules cause larger beam divergence, and the scattering aggravates with increasing pressure.

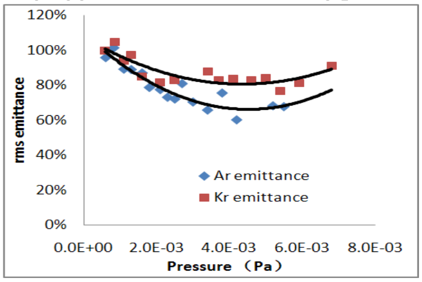

Figure 4: Emittance variation in Kr and Ar compensation. All data is compared with the emittance value without extra gas injection.

DATA PROCESSING

The ECGI energy spectra and the beam profiles include more information than those listed above. The potential distribution in the beam can be calculated from energy spectra and the beam profiles [4]. Sequentially, according to the Poisson function the rest charge distribution can be calculated from the potential [8]. The rest charge density *n(rest)* meet the following function

$$n(rest) = n(b)+n(i)-n(e) \qquad (2)$$

where *n(b)* is the density of beam ions, *n(i)* is the density of ECGIs and *n(e)* is the density of electrons. In the calculation n(i) is considered to be zero because most low energy ECGIs will be repelled out of the beam rapidly. Five groups of results are given in Fig. 5, separately for no extra gas injection, Ar pressure of 3.0×10^{-3}Pa, Ar pressure of 4.5×10^{-3}Pa, Kr pressure of 2.0×10^{-3} Pa and Kr pressure of 3.0×10^{-3} Pa.

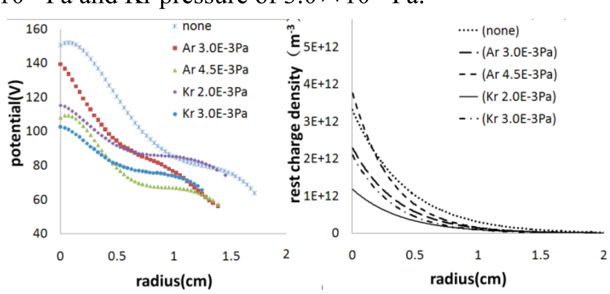

Figure 5: (a)Beam potential distribution, fitted by polynomial. (b)rest charge density distribution, fitted by indicial equation.

From Fig. 5(a), although the PBC is lower in Kr compensation than that in Ar compensation, the beam edge potential has an opposite performance. In other words, the beam potential in Kr compensation has a flatter distribution. Flat distribution leads to smaller space charge force which is proportional to the derivative of the potential.

The beam ions have the density on the order of 10^{14} m^{-3}. Fig. 5(b) shows the rest charge density is on the order of 10^{12} m^{-3}. That means the SCC effect reduced the charge density significantly by 2 orders. Increasing extra gas injection results in decreasing rest charges, and Kr seems more efficient. With the same pressure of 3×10^{-3} Pa, Kr compensation has only half the rest charge density than that in Ar compensation. This result echoes the superiority of Kr in generating more electrons shown in the ECGI energy spectra measurement.

CONCLUSIONS

Experimental results presented in this article provide a general view of SCC effect in Low energy high intensity H^+ beams. Analysis of these results draws three conclusions as following.

- At a pressure of 3.7×10^{-4} Pa,SCC effect with residual gas in the beam pipe can compensate more than 90% of the beam charge. Even so, suitable electronegative gas injection improves the beam quality evidently, including reducing the rest charge to one third, controlling the emittance increase, lowering the beam potential and focusing the beam.
- As the compensation gas, Kr is more efficient than Ar in terms of electron generating, improving the beam distribution and reducing the beam potential and the space charge force. However, in controlling the beam emittance Ar is 20% better than Kr.
- A large injection of gas does not always benefit the beam quality. Too high a pressure leads to little improvement in electron generation and the beam profile, instead there is an obvious rising of emittance. The molecular weight and amount of gas molecules are considered the main factors which determine the scattering strength. So the best SCC condition is not constant but depends on the specific demand of the beam.

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