

SPACE CHARGE NEUTRALIZATION STUDIES WITH H⁻ BEAM IN LOW ENERGY BEAM TRANSPORT TEST STAND

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Abstract

Japan Proton Accelerator Research Complex (J-PARC) is intensity-upgraded up to pulse current of 50 mA of H⁻ beam. Two-solenoid based Low Energy Beam Transport (LEBT) test stand is being built to support the operation of J-PARC linac. It imitates the actual LEBT of linac, yet contains the diagnostics chamber composed of horizontal and vertical beam emittance-meters and Faraday-cup for the current measurement. Vacuum composition of LEBT is predominantly H₂ gas. The pressure inside the LEBT can be varied by the differential pumps allowing us to study the beam phase space evolution under space charge effects. The measurements of the beam phase space emittance were made as a function of the residual gas pressure. This paper presents the results and discussion on beam space charge neutralization and its effect on the beam phase space emittance.

INTRODUCTION

Two solenoid based LEBT of J-PARC linac transports a negative hydrogen beam at 50 keV from ion source into the RFQ [1]. Due to large amount of H₂ gas load coming from ion source, the residual gas component in the LEBT is mainly H₂ molecules. An aperture with 15-mmφ was designed and set in between two solenoids of LEBT to maintain a pressure level of ≈1.7×10⁻⁵ Pa at the upstream of the RFQ. In the region of LEBT starting from ion source exit till 15-mmφ aperture, the pressure level is ≈3.7×10⁻⁴ Pa.

Space Charge Neutralization Factor of H⁻ Beam Pulse

Positive residual gas ions will be produced in collisions of H₂ molecules with high intensity H⁻ beam. H₂ molecules are as a target in this collision hit by 0.01 light speed H⁻ beam. The number of liberated residual gas ions in a given volume is proportional to the density of the incident beam. Accumulation of H₂⁺ ion rate can be calculated from the pressure, the residual gas composition and the impact-ionization cross section σ(v). Along the trajectory of H⁻ beam, the change of line density of positive H₂⁺ ions λ_r(s) can be calculated as:

$$\dot{\lambda}_r(s) = \sigma(v) \cdot n \cdot \dot{N} \quad (1)$$

where n is density of residual gas, determined by the pressure, Ṅ the number of positive ions per time unit. The space charge neutralization factor can be defined as the ratio of:

$$\eta = \left| \frac{\lambda_r(s)}{\lambda(s)} \right| \quad (2)$$

where λ(s) describes the line density of incident H⁻ beam. For a pulsed ion beam with: I(t) = Î during the time interval of 0 < t ≤ T_p and I(t) = 0 when T_p < t, we obtain the residual gas density for 0 < t ≤ T_p with the following equation:

$$\lambda_r(t) = \int_0^t \dot{\lambda}_r dt' = \sigma(v) \cdot n \cdot \frac{\hat{I}}{e} \cdot t \quad (3)$$

where Î pulse height, T_p pulse length, e elementary charge. Taking into account the equations 2 and 3, the time dependence of the space charge neutralization factor can be shown as:

$$\eta(t) = \sigma(v) \cdot n \cdot v(s) \cdot t \quad (4)$$

According to the equation 4, the neutralization factor increases linearly until t = T_p or η = 1 which means the beam is 100% space charge neutralized. It occurs when each H⁻ ion is at the same location of one H₂⁺ neutralizing particle. As shown in Fig. 1, we calculated the neutralization factor as a function of time for baseline pressure of LEBT. Cross section for the impact ionization of hydrogen molecules can be derived in good approximation from well known H₂ target ionization cross section by protons [2]. The cross section for the rest gas ionization is, to a large extent independent of the sign of the charge and is a function of velocity of singly charged particle if the velocity is higher than 1% speed of light [2]. Hence, in our calculation we assume that σ(v) ≈ 2 · 10⁻¹⁶ cm² and beam pulse length is 0.7 ms.

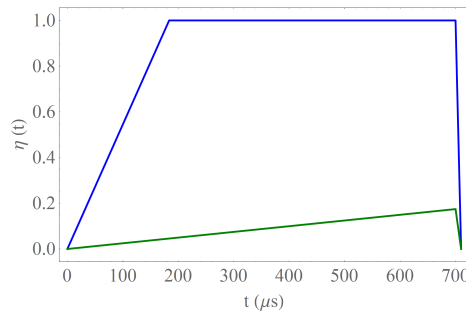


Figure 1: The space charge neutralization factor as a function of time at baseline pressure of 3.7×10⁻⁴ Pa for upstream of LEBT (shown as a blue line) and 1.7×10⁻⁵ Pa for downstream of LEBT (shown as a green line). The blue curve shows, the time required for reaching η(t)=1 at 3.7×10⁻⁴ Pa for upstream of LEBT is 183 μs. The green curve shows, at 1.7×10⁻⁵ Pa pressure only 10% space charge neutralization degree can be achieved during 700 μs, that is η(t)=0.1.

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At test stand, the pressure level in downstream of LEBT is changed by closing the gate valves in order to equalize it to the pressure level of upstream LEBT. Figure 2 shows the calculation of neutralization factor as a function of time for increased pressure level of LEBT. Linear increase of $\eta(t)$ curve shows the characteristic time that how fast the space charge neutralization can be built-up at a given gas pressure. The speed and degree of space charge neutralization depends on the residual gas composition and pressure. In 1.7×10^{-5} Pa pressure, the linear increase of $\eta(t)$ curve is slow, it leads only a partial compensation of beam space charge field. When $t > T_p$ the beam pulse is over, $\eta(t)$ decreases to zero in a very short time. For further studies, measurements of the beam phase space emittance were obtained as a function of different H₂ gas pressures in LEBT test stand.

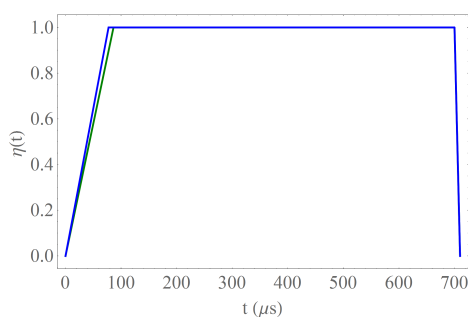


Figure 2: The space charge neutralization factor as a function of time at pressure of 8.9×10^{-4} Pa for upstream of LEBT (shown as a blue line) and 7.99×10^{-4} Pa for downstream of LEBT (shown as a green line). The time required for reaching $\eta(t)=1$ is $78 \mu s$ and $94 \mu s$, relatively.

TRANSVERSE EMITTANCE MEASUREMENTS AT LEBT TEST STAND

Experimental setup of LEBT test stand consists of the horizontal and the vertical beam emittance monitors, Faraday cups, two solenoid magnets, a steerer magnet for the beam trajectory correction and a gate valve. Beam properties were measured by means of Faraday cup for beam current and emittance monitors for transverse beam phase space. The beam signals from the emittance monitor can be sampled with a resolution of $1 \mu s$ (or $5 \mu s$, $10 \mu s$) allowing the measurements of intensity and phase space to be made as a function of time. Observation of beam phase space in every $1 \mu s$ of $\sim 700 \mu s$ beam pulse length gives detailed information on phase space evolution of the beam in LEBT. Figures 3 and 4 show the examples of the horizontal beam emittance measurement with 50 mA and 30 mA currents at the same baseline pressure of LEBT test stand. Space charge forces has defocusing effect on the beam, therefore the comparison of phase space evolution of the beam as a function of time at different intensities is made. Figures 4 and 5 are the examples of horizontal beam emittance measurement with 30 mA current at different pressure levels.

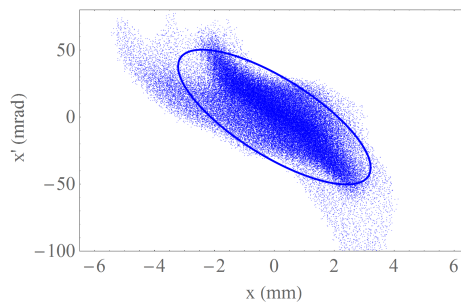


Figure 3: Horizontal emittance of H⁻ beam measured with 50 mA current at baseline pressure of LEBT. Calculated rms emittance (26.69 mm·mrad) is shown as phase space ellipse.

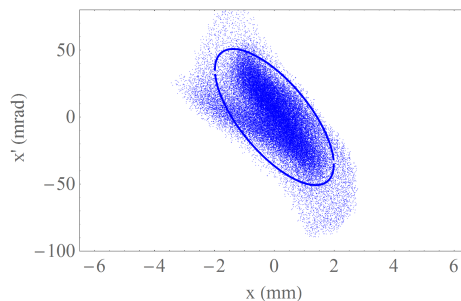


Figure 4: Horizontal emittance of H⁻ beam measured with 30 mA current at baseline pressure of LEBT. Calculated rms emittance (18.09 mm·mrad) is shown as phase space ellipse.

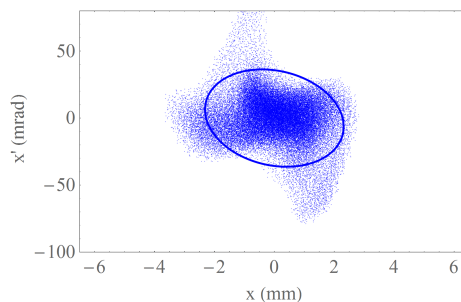


Figure 5: Horizontal emittance of H⁻ beam measured with 30 mA current at 8.9×10^{-4} Pa and 7.99×10^{-4} Pa pressure of upstream and downstream of LEBT. Calculated rms emittance (20.68 mm·mrad) is shown as phase space ellipse.

Complete measurements show the influence of the pressure on the time required for space charge build-up process for H₂⁺ and H⁻ ions. Due to many parameters such as, the ion source and extraction electrode system, the rise time of the beam current from the source and nonlinearities make the experimental setup in LEBT more complex. Beam halo in transverse emittance measurements is assumed the cause of nonlinearities and maybe can be reduced by optimizing the settings in further experiment.

Twiss Parameter as a Function of Time

Twiss parameter α is a relevant parameter to describe the space charge effects on the beam phase space evolution. Beam twiss parameters vary considerably due to a rotation

of phase space during the pulse in the space charge regime until beam is fully neutralized. If beam is partially neutralized and also the phase space varies by time significantly, this complicates the beam matching of the front end for pulsed beams. J-PARC linac LEBT baseline pressure is limited to $\sim 10^{-5}$ Pa in order to avoid high pressure in the RFQ. Concurrently, at the exit of ion source LEBT maintain $\sim 10^{-4}$ Pa pressure level. Both pressure levels are co-exist and considered as the baseline pressure of LEBT partitioned by 15-mm ϕ aperture. This means, the beam exiting the ion source experiences with higher pressure and passes across the 15-mm ϕ aperture then experiences with lower pressure while matched into the RFQ acceptance. Figure 6 shows the plot of Twiss parameter α analyzed from the emittance measurements of 30 mA H⁻ beam current as a function of time. Blue dots are data, sampled in every 1 μ s, from the measurement obtained at baseline pressure of LEBT test stand. Green dots are data from the measurement where upstream and downstream LEBT pressure is equalized, 8.9×10^{-4} Pa and 7.99×10^{-4} Pa, relatively. Data is sampled in every 1 μ s until 145 μ s and in every 10 μ s for further. It can be seen that, the rotation of beam phase space becomes stable after ~ 100 μ s (green dots) and after ~ 200 μ s (blue dots). These are required time for space charge neutralization at a given pressure and conditions in which beam reaches stable state. Required time is calculated as ~ 94 μ s (for green dots) and ~ 183 μ s (for blue dots).

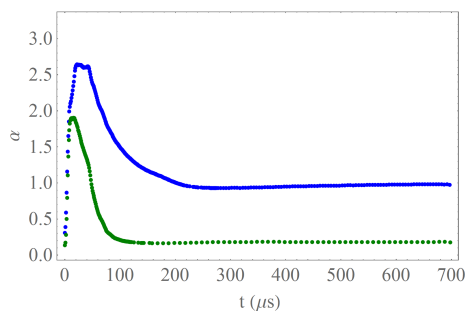


Figure 6: Twiss parameter α as a function of time. α is determined from the horizontal emittance measurements of 30 mA H⁻ beam at two different pressure levels.

Figure 7 shows the plot of Twiss parameter α analyzed from the emittance measurements of 30 mA and 50 mA H⁻

beam current as a function of time. Both data were obtained with 8.9×10^{-4} Pa and 7.99×10^{-4} Pa, and sampled in every 1 μ s until 145 μ s and in every 10 μ s for further. Increasing the pressure reduces the time required for beam phase space to reach the stable state. Results show that, the beam with higher intensity requires slightly longer time to stabilize the phase space variation under space charge compared to the beam with lower intensity. Beam phase space variation is obvious in all measurements at the beginning of pulse during space charge build up.

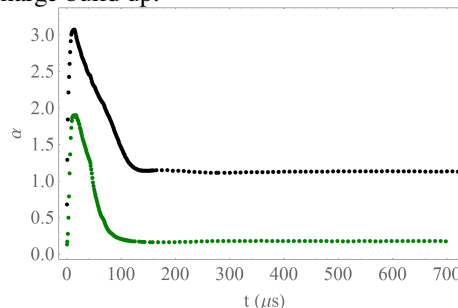


Figure 7: Twiss parameter α as a function of time. α is determined from the horizontal emittance measurements of 30 mA and 50 mA H⁻ beam at the same pressure of LEBT test stand. Green dots are data from the measurement with 30 mA and black dots are data from the measurement with 50 mA H⁻ beam.

CONCLUSION AND OUTLOOK

When beam is space charge neutralized the phase space of the beam becomes stable. We observe a slow variation of beam phase space as a function of time at baseline pressure of LEBT. Beam can be matched and accelerated starting from the stable part. This can be accomplished by setting a delay in RF system. At test stand measurement we employ 700 μ s pulse and only 500 μ s is required for the acceleration.

REFERENCES

- [1] J-PARC website, <http://j-parc.jp/index-e.html>
- [2] M. Reiser, "Ionization cross-sections for electron and proton beams in various gases", in *Theory and Design of Charged Particle Beams*, Weinheim, Germany: Wiley, 2008, pp. 243–246.