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BEAM LOSS SUPPRESSION BY IMPROVEMENT OF VACUUM SYSTEM IN J-PARC RCS

J. Kamiya#, M. Kinsho, S. Noshiroya, K. Yamamoto, JAEA/J-PARC, Tokai, Naka, Ibaraki, Japan

Abstract

In 3GeV synchrotron of J-PARC, the injection line called L3BT line (Linac to 3GeV synchrotron Beam Transport line), is the section, where the high beam line pressure causes the beam loss. In this section, H^- beam from Linac was converted to H^0 by charge stripping due to the interaction between H^- beam and the residual gas molecules. Such H^0 beam was not bended by the injection septum magnets and directly hit the vacuum wall. Additional vacuum pumps were installed in this section to reduce the beam line pressure and beam loss in this section. By installing two turbo molecular pumps, the beam line pressure was reduced by double-digit. The beam loss due to the charge stripping of the injection beam was able to be suppressed.

INTRODUCTION

In high power beam accelerators, the pressure of the beam line directly affects the amount of the beam loss. For example, in the early 1970's in CERN's Intersecting Storage Ring (ISR), the pressure bump produced the fall-off of the beam current [1,2]. This phenomenon was triggered by the ions, which were produced by the interaction of the residual gas and the beam. The ions, which are accelerated by the beam potential, bombard the chamber wall and knock off molecules, which have been adsorbed on the surface. Since the ion bombardment increase the pressure and the pressure increases the ion bombardment, this leads to an avalanche process. The other phenomenon was observed in BNL AGS Booster [3]. They examined the effect of the beam line pressure on the life time of Au^{31+} beam. They showed that the beam life time, which was dominated by electron stripping process, was inversely proportional to the average pressure.

3GeV synchrotron (Rapid Cycling Synchrotron: RCS) in J-PARC is no exception. RCS is one of the most high power beam accelerators in the world. It aims the 1MW beam power, which corresponds to the average and peak beam current of 333 μA and about 10 A, respectively. In the present stage, the injection line called L3BT line (Linac to 3GeV synchrotron Beam Transport line), is a section, where the beam line pressure notably produces the beam loss. Figure 1 shows the layout of L3BT near the injection section of RCS. H^- ions from Linac, whose energy is 181 MeV until 2013 and 400 MeV from 2014, was normally converted to H^+(proton) by charge stripping foil at injection point in RCS. In L3BT line, H^- ions were inconveniently converted to H^0 atoms (and small amount of H^+) due to the interaction between H^- ions and the residual gas molecules. Such H^0 atoms are not bended by the injection septum magnets and directly hit the vacuum wall. The residual dose rate around the injection branch is notably higher than the other points, which is consistent with above explanation.

We decided to add the vacuum pumps in this section to reduce the residual gas molecules in the beam line. In this paper, first, we will present the expected effectiveness of the additional pumps on the beam line pressure by a calculation. Next, we will show the measured results of the beam line pressure improvement and the beam loss suppression.

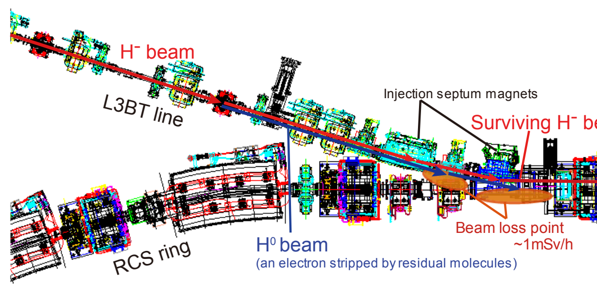

Figure 1: Layout of L3BT line near the injection section of RCS. The possible mechanism of the beam loss is also shown.

INSTRATION OF ADDITIONAL PUMPS

Adoption of Turbo Molecular Pump

Unlike sputter ion pumps, non-evaporated getter pumps, cryogenic pumps, etc., which apply adsorption and/or burial of gases as the pumping principle, turbo molecular pumps (TMP) can continuously pump gasses and does not become saturated. There are some vacuum apparatus which have relatively large outgassing rate in RCS, like kicker magnets, carbon foils for charge exchange, and beam collimators [4-6]. Therefore, the TMP have been used for main pumps in RCS beam line [7]. The TMP used in RCS are those, which had been developed for the radiation resistance by Japan Atomic Energy Agency and Osaka Vacuum Ltd [8]. Because the radiation resistance of TMP in L3BT line is also important by necessity, the same type of TMP is adopted for the additional pumps. Figure 2 shows a schematic block diagram of a TMP unit. Main tunnel is high-radiation area during beam operation, while the utility tunnel is low-radiation area. Dry scroll pumps (DSP) are used as fore pumps and installed in the utility tunnel in order to prevent the workers' exposure by scattered radiated chip seal powders during the maintenance.

#junichiro.kamiya@j-parc.jp

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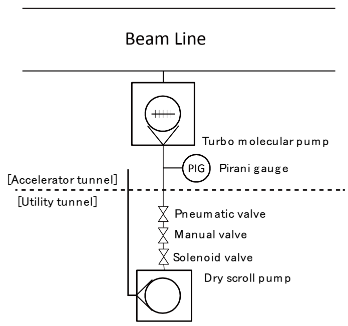

Figure 2: Schematic block diagram a turbo molecular pump unit.

Estimation of Effectiveness of the Additional Pump

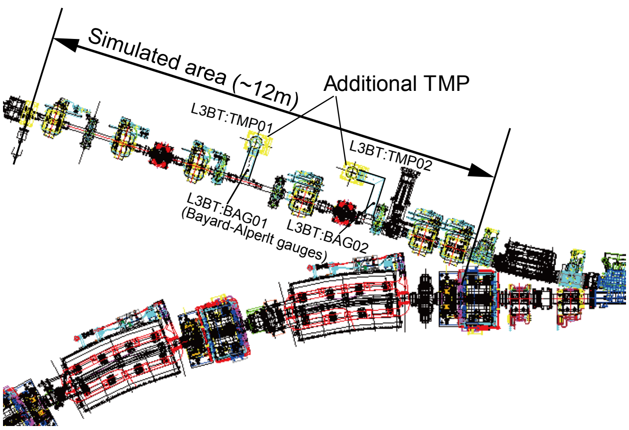

Figure 3: Arrangement of turbo molecular pumps in L3BT line. The area, which was simulated by the calculation code, was also shown.

Two TMP units are installed in L3BT line as shown in Fig. 3. The TMP and the beam line are connected by vacuum pipes and bellows. The conductance of these pipes for air is about 500 l/s and 370 l/s for the upstream and downstream TMP, respectively. The beam line pressure is about 10^{-5} Pa before installing the additional pumps. The pressure, which should be achieved by the additional pumps, is estimated as follows. The charge exchange efficiency at injection point is 99.6 % with 200 μg/cm^2 thick carbon foils [9]. This means that 0.4 % H^- are not accurately exchanged to H^+ at the injection point. H^-, which are charge exchanged at L3BT line and are not accurately exchanged to H^+ at the injection point, should be much smaller than this value. In order to examine the effectivity of the additional pumps, we set the criterion that the charge exchange efficiency at L3BT line should be $4 \cdot 10^{-6}$, which is less than 1/1000 of above value. The number of H^- (N), which is exchanged to H^0 (and H^+), is calculated as

$$N = \sigma \ \rho L N_{beam},$$

where σ is the charge exchange cross section, ρ is the molecules density, L is the length of the beam line, N_{beam} is a number of H^-, which is injected to L3BT line. The molecules density ρ is written as

$$\rho = \frac{P}{kT},$$

where P is the beam line pressure, k is the Boltzmann constant, and T is the absolute temperature. For the cross section σ, the equation in the reference [10], which derived from the measured value, is used and estimated to $\sigma = 2.038 \cdot 10^{-22}$ m^2 at 181 MeV. The equation in [10] is estimated for the carbon, nitrogen, and oxygen as the targets. The main residual gas in the L3BT line is hydrogen. Therefore the actual cross section is smaller than the calculated value, which means the estimated pressure is stricter. The length of the beam line L, is 12 m. By using above equations, the target pressure is estimated to less than $6.8 \cdot 10^{-6}$ Pa.

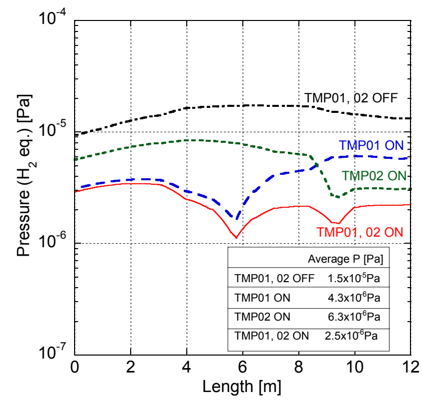

Figure 4: Pressure distribution which is calculated by the code VASCO. The dotted and solid line represents the pressure (H_2 eq.) without and with the additional pumps.

The pressure distribution was calculated by the code VASCO (VAcuum Stability COde), which is developed by CERN in order to calculate both the static and dynamic pressure distribution [11,12]. In our case, the statistic case was calculated. Input parameters are the shape of the beam pipes, their outgassing rate, and the pumping speed of their position. The inner diameter and the length between flanges were input for the shape of the beam pipes (and bellows). The main residual gas in L3BT line is hydrogen, which was measured by the residual gas analyser (see the next section). Thus only hydrogen outgassing rate and pumping speed were took into account for the calculation. The measured outgassing rate per unit are of the titanium without bake-out, which is $6 \cdot 10^{-7}$ Pa m^3/s/m^2 (H_2 eq.) was used for the normal beam pipes. For the bellows and monitors, however, which have larger amount of outgassing rate, the six-fold to tenfold outgassing rate of titanium was input. The pumping speed at the upstream and downstream border was estimated from the pumping speed of the nearby pumps and the conductance between the borders and the pumps. Figure 4 shows the calculated pressure distribution without and with the additional pumps. By installing the two turbo molecular pumps, the lower level of 10^{-6} Pa or less pressure is achieved all over the simulated beam line area. The average pressure is $2.5 \cdot 10^{-6}$ Pa. It is expected that the target pressure could be achieved and the beam loss due to the unwanted charge exchange in L3BT line would be reduced by the additional pumps.

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PERFORMANCE EVALUATION

Improvement of Vacuum

In order to investigate the effectiveness of the additional pumps, the pressure measurement was performed. The beam line pressure was measured by the Bayard-Alpert gages, which were installed nearby each TMP as shown in Fig. 3. The partial pressure was measured by the quadrupole residual gas analyser, which is located nearby TMP01. The measurement was started from the status, where the two TMP were normally operated. After that, each TMP was stopped in series. The pressure was measured in each case 10 min after stopping the TMP. Figure 5 shows the results. With two TMP, the beam line pressure become the lower level of 10^{-7} Pa, while it was the lower level of 10^{-5} Pa without TMP. For the partial pressure, there were peaks of hydrogen, which was the main peak, and water vapour in the mass spectrum. Their ion current were compared in Fig. 5. Almost only hydrogen remains by operating two TMP. With two TMP ON, the amount of hydrogen become less than 20 % of TMP OFF case.

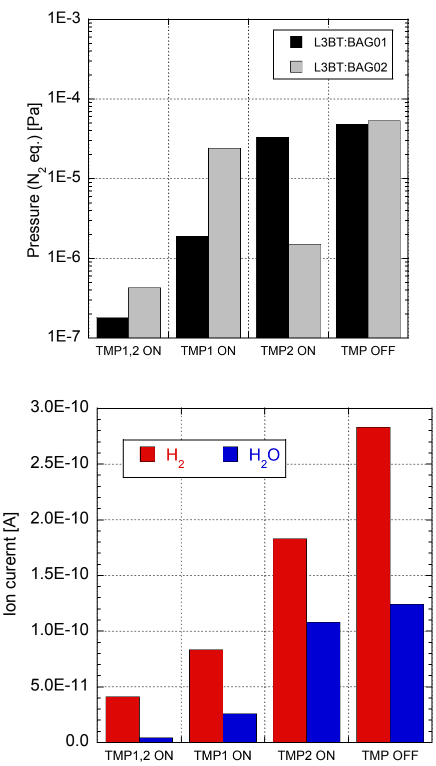

Figure 5: Measured beam line pressure in each case with and without additional TMP.

Beam Loss Reduction

The effectiveness of the additional pumps on the beam loss was also investigated in each cases, where the two TMP were operated or not. Figure 6 shows the signal of the beam loss monitor (plastic scintillator), which is located at the inner periphery of the injection branch.

There is clear relation between the beam loss and beam line pressure as expected. Due to the additional TMP, the beam loss was reduced about one-fifth of the case without additional pumps.

For the residual dose, it is difficult to compare quantitatively before and after installing the additional pumps because the beam energy was different: 181 MeV before and 400 MeV after installing the additional pumps. However, the results of the dose measurement just after beam operation showed that the residual dose was reduced from a few mSv/h to 750 μSv/h despite the higher beam power operation [13].

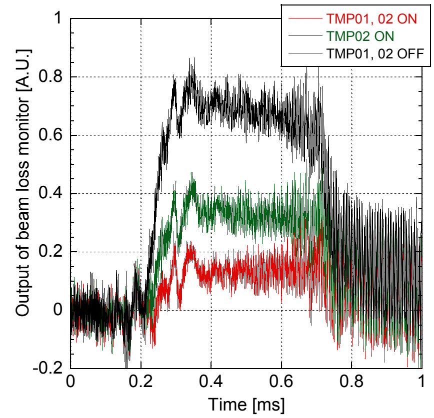

Figure 6: Measured beam loss signal in each case with and without additional TMP.

SUMMARY

Two turbo molecular pump units were installed in the injection line of RCS in order to improve the beam line pressure, which had been the origin of the beam loss in this section. The lower level of 10^{-7} Pa beam line pressure was locally achieved by the additional pumps, and the beam loss was reduced about one-fifth.

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