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SPACE CHARGE SIMULATION AND MATCHING AT LOW ENERGY SECTION OF J-PARC LINAC

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Abstract

An intensity upgrade of Japan Proton Accelerator Research Complex (J-PARC) included the installation of a new ion source (IS) and a radio-frequency quadrupole (RFQ) which to be used at first stage of acceleration. The linac is divided into two sections on the basis of operating frequencies and three sections on the basis of family of RF cavities to be used for the acceleration of 50 mA beam of H^- ions from 50 keV to 400 MeV. Low energy part of linac consists of an IS, a two-solenoid beam transport (LEBT) and the RFQ. The transition from one section to another can limit the acceptance of the linac if these are not matched properly in both longitudinal and transverse plane. Initially, we have calculated the acceptance of the RFQ at zero current in which space charge effects are not considered. In addition, a particle tracking technique is employed to study the space charge effects in LEBT of the J-PARC linac after the intensity upgrade in order to match the beam to the RFQ. Also, RFQ tank level and intervene voltage calibration factor is determined by comparing the simulation results of the beam transmission with the test measurement of tank level vs. transmission.

INTRODUCTION

J-PARC - the Japan Proton Accelerator Research Complex is a high intensity proton accelerator facility located at Tokai village in Japan [1]. A new linac front-end had been installed for intensity upgrade in 2014, July-September [2]. It consists of a 50 keV IS, a two-magnetic solenoid based LEBT and 324 MHz RFQ accelerating H^- beam to 3 MeV. To support commissioning of J-PARC linac, General Particle Tracing (GPT) code [3] is used for H^- beam dynamics simulations. The particle tracking technique using 3D field-maps is a convenient tool to study the charged particle dynamics in electromagnetic fields. The goal is to optimize beam quality and transmission through the accelerator and to prepare the beam for the next section. For high intensity, low energy ion beams the electric field created by space charge reveals defocusing effect and is non-linear as induced by the non-uniform distribution of charge density. This defocusing effect can be compensated by transporting the low energy beam in space charge neutralization regime. Here we discuss the process of creating a partially-neutralized beam and examine the effects of space charge on the beam emittance. For optimizing the beam matching to the RFQ transverse emittance measurements are also used in simulations. RFQ acceptance with zero current and taking into account the space charge is determined. RFQ tank level and intervene voltage calibration factor is found by comparing the simulation results of the beam transmission with the measurement of tank level vs. transmission.

LEBT

Low energy part of linac consists of an IS, LEBT and the RFQ. The length of LEBT is approximately 566 mm. It consists of two short solenoid magnets, a gate valve and a diagnostic chamber which has a vacuum partition plate with an orifice of 15 mm. The solenoid magnets can produce a magnetic flux of 1.1 T. Solenoid based magnetic focusing transport system has been confirmed to be superior for the injection of the RFQ used to accelerate H^- beams. In the transport of high current low energy ion beams the space charge forces are most prominent. In the LEBT, the H^- beam traverses a region containing H_2 background. The vacuum level at upstream and downstream of LEBT is 3×10^{-3} Pa and 2×10^{-5} Pa, relatively. H^- beam and H_2 interaction is possible in two channels: detachment of an electron from the beam and ionization of the H_2. The compensation of space charge effects by charge neutralization using secondary particles produced in the interaction between ion beam and residual gas can significantly reduce the required focal strength and reduce emittance degradation.

Transverse Beam Emittance Measurement from IS Test Stand

At IS test stand a slit-and-grid emittance-meter located after the first solenoid and measurements for 66 mA beam were taken. The horizontal and vertical emittances are measured by using two sets of W-slit emittance monitors, each of them is composed of a movable slit and a movable Faraday-Cup with slit (FCS) [4]. Each slit has an opening of 0.1 mm. The measured emittance is visualized by randomly plotting dots, whose number is proportional to the current detected by the FCS and is normalized to make the total number 10 000, in each mesh area defined by the moving steps (0.2 mm and 2 mrad) and the positions of the slit and the FCS. 3D raw data analysis is shown in Fig. 1. To suppress the background noise, an arbitrary threshold is applied to cut off some data. Obviously, this can effect the tail of the beam. Gray area shows where the intensity is higher than the threshold and the main part of particles are situated approximately in this area. The knowledge of beam phase space at the IS exit is essential for transverse matching of the beam into the RFQ. For this reason, an algorithm to reconstruct the beam phase space distribution from emittance measurement developed and can be used to find the optimized solenoid settings for transverse matching. 3D field maps of solenoid magnets and the RFQ are calculated by CST EM Studio Suite.

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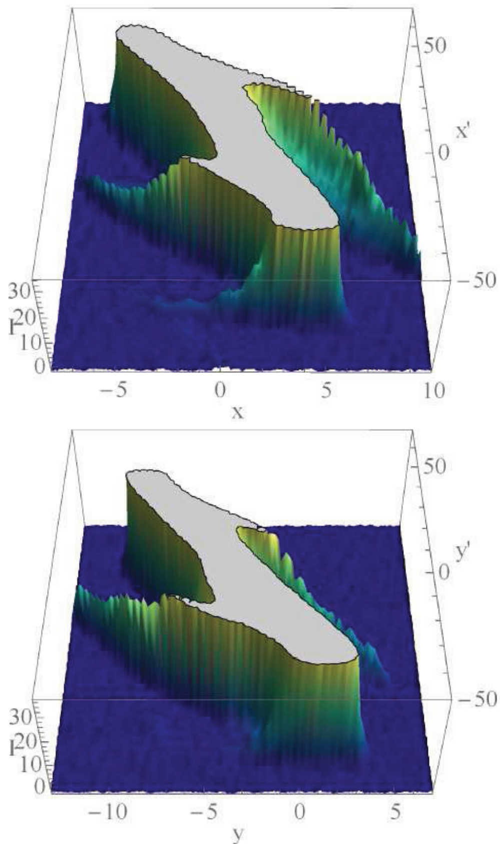

Figure 1: Transverse emittance measurement from IS test stand, where x,y in (mm), x′, y′ in (mrad) and the emittance monitor′s signal, I in arbitrary units.

Beam Back-Tracking Simulation

In our simulations, solenoid magnet has a 130-mm radius, 105-mm length and 45-mm fringe fields. The distance between 2 solenoids in LEBT is 356 mm. By using GPT code, the emittance measurement data is tracked back to IS exit through the solenoid field. In the IS test stand, a high degree of space charge compensation (about 95%) could be concluded indirectly from measurements. Corresponding vacuum level was 1.24×10^{-2} Pa. When the space-charge neutral equilibrium is reached, the beam has close to zero space-charge effects and hence would travel a path similar to the equilibrium state. Due to different vacuum level at the upstream and the downstream of LEBT, the beam is better neutralized in first half of the LEBT. The degree of compensation has been determined to be in the range of 95% in equilibrium by comparison of experimental results with simulations. An experimental program has been scheduled to investigate the detailed dynamic process of space charge compensation for H^- beam in the downstream of LEBT.

Matching

Emittance measurements together with transmission measurements are essential for the correct setup of linac during the commissioning phase. This implies an accurate measurement of the emittance and the beam transverse twiss parameters at different vacuum levels. Simulation results show, that the emittance requirements at the entrance of RFQ are: rms emittance is between (0.412 - 0.25) π mm·mrad at injection energy of 50 keV. These values are determined from simulations using zero current and the design current with full space charge. To set the right value depends on space charge compensation in LEBT. To meet this requirements, IS and LEBT have to be tuned well but not many data about LEBT transmission are available at present. A new Test Stand (TS) is being built to perform a detailed experimental analysis of space charge compensation as a more detailed knowledge is of interest for high power proton linacs. We have plan to evaluate the influence of H_2 density in LEBT by using TS where we can alternate the pressure.

RFQ ACCEPTANCE DETERMINATION

Initially, a uniform, rectangular phase space and spatial beam distribution is applied into the RFQ entrance to be traced in order to determine zero current acceptance. From the simulation result, the maximum phase space ellipse is calculated to be 0.412 π mm· mrad which gives the highest beam transmission. Twiss parameters of the phase space ellipses are also defined. GPT code provides a built-in method to calculate the space charge based on non-relativistic point-to-point interaction. Assuming no space charge compensation for 50 mA for H^- beam current at 50 keV, RFQ acceptance is determined with full space charge effects. RFQ acceptance ellipses at horizontal and vertical planes for zero current and 50 mA current considering full space charge effects are shown in Fig. 2 and in Fig. 3. RFQ acceptance is determined to be 0.25 π mm·mrad for 50 mA H^-beam current if there is no space charge compensation. Practically, these ellipses calculated for two different conditions are boundary values of RFQ acceptance. Depending on space charge compensation regime in LEBT, beam emittance will be matched within these values.

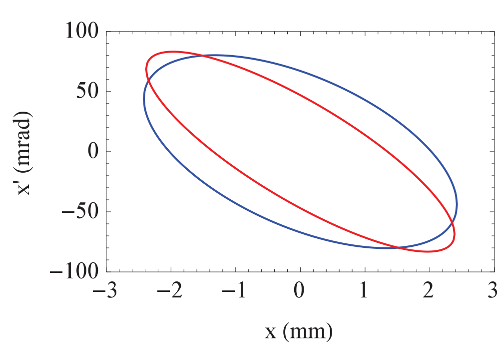

Figure 2: RFQ acceptance in horizontal plane. Blue ellipse represent the zero current acceptance and red ellipse represent the acceptance for 50 mA current with full space charge effects.

RFQ TRANSMISSION

By using a random particle generator in Mathematica [5], a uniform, hyper-ellipsoid distribution is created within the

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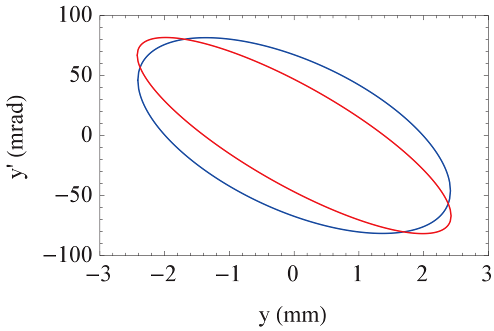

Figure 3: RFQ acceptance in vertical plane. Blue ellipse represent the zero current acceptance and red ellipse represent the acceptance for 50 mA current with full space charge effects.

RFQ acceptance. It is essential to generate random points uniformly distributed in a hyper-ellipsoid to represent H^- beam. An example of the simulation input, 50 keV H^- beam distribution is shown in Fig. 4. Input beam geomet-

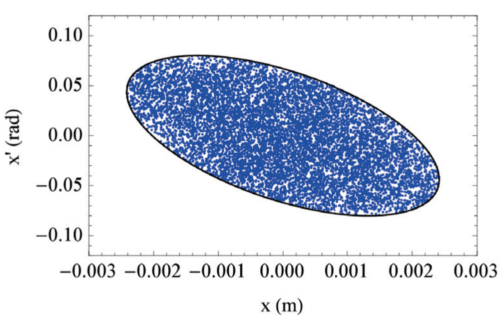

Figure 4: Input beam distribution in horizontal plane for RFQ transmission simulation.

rical emittance is 162 mm·mrad (with twiss parameters of α=0.6547 rad, β=0.036 m, normalized rms emittance of 0.412 π mm·mrad). For zero current acceptance, ~97% beam transmission is obtained. GPT built-in space charge routines provide numerical estimation of beam dynamics for 50 mA current beam with an arbitrary number of RF periods long with finite initial momentum spread. RFQ acceptance for 50 mA H^- beam with no space charge compensation is determined to be 112 mm·mrad (where twiss parameters are ~α=1.44 rad, β=0.05 m, normalized rms emittance of 0.25 π mm·mrad) which gives ~50 mA current at the exit of RFQ . Measured RFQ transmission as a function of tank level using 5 mA H^- beam is shown in Fig. 5. Maximum beam transmission is achieved at 108% high voltage. Particle tracking simulation using zero current beam distribution as a function of RFQ intervane voltage is performed in order to determine the calibration factor of tank level $\propto$ intervane voltage. Comparison of the simulation result and measurement is shown in Fig. 6, hence the calibration factor is determined to be 0.902 kV/%.

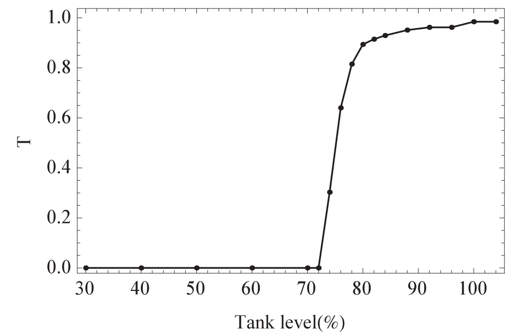

Figure 5: Measurement of the RFQ transmission as a function of tank level, performed using 50 keV H^- beam with 5 mA of beam current.

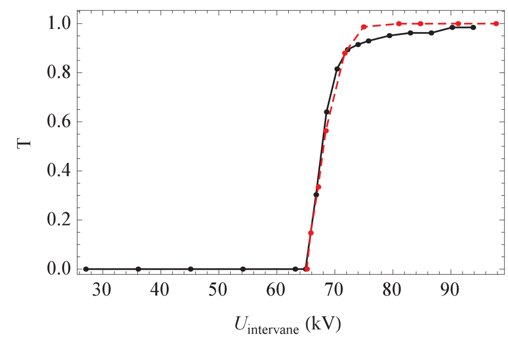

Figure 6: Comparison of simulation and measurement of the RFQ transmittance. The black, solid line is the RFQ transmission measurement as a function of tank level, performed using 50 kV H^- beam with 5 mA of beam current. The red, dashed line is the simulation result of zero current transmission as a function of RFQ intervane voltage.

CONCLUSION AND OUTLOOK

Development of emittance and twiss parameters as a function of time for the beam at nominal pressure is investigated for transverse matching in LEBT, after the intensity upgrade of the J-PARC linac. The particle tracking technique is employed to study space charge effects at 5 mA, 30 mA and 50 mA H^- beam currents. Also, an algorithm is developed to reconstruct the beam phase space at the IS exit using the emittance measurement data taken from IS test stand. This beam distribution is loaded into the simulation as an initial condition of a higher-current (61 mA) for adjusting the solenoid strength in the LEBT. We have plan to evaluate the influence of H_2 density in LEBT experimentally, by using TS where we can alternate the pressure.

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