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DIRECT MEASUREMENT OF THE LONGITUDINAL EMITTANCE FOR A PROTON BEAM AT EXIT OF A RADIO FREQUENCY QUADRUPOLE*

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Abstract

In this contribution, we introduce a method for direct measurement of the longitudinal emittance of a proton beam at the RFQ exit, which delivers an output energy of 1.52 MeV. Initially, we developed a bunch shape monitor (BSM) inspired by Feschenko's design, achieving a resolution of 20 picoseconds. To conduct the direct measurement of longitudinal emittance, we integrate this BSM with a waist-to-waist beam transfer matrix, an energy-spread dipole, and a horizontal slit with a 0.2 mm width. The horizontal slit is positioned at the first waist at the dipole's input, while the BSM wire is situated at the second waist, at the dipole's output. This arrangement, enhanced by the waist-to-waist transfer matrix, improves the energy spread resolution to 0.03%. Through adjusting the buncher voltage and synchronous phase, we use dipole and BSM to measure different longitudinal emittances and ascertain the effects of bunching and debunching conditions on the longitudinal phase space distribution.

INTRODUCTION

The longitudinal phase space distribution refers to the distribution of particles in both phase and momentum along the direction of beam propagation. The RFQ serves as an important component in the linac, responsible for bunching and accelerating the beam. Understanding the longitudinal phase space distribution at the exit of a radio frequency quadrupole (RFQ) is crucial for precise beam tuning and minimizing beam loss in a high-power superconducting linac [1]. Here we introduce a direct measurement of longitudinal emittance by a developed bunch shape monitor (BSM), a wasit-to-waist beam transfer line, a dipole energy spread magnet and a horizontal slit in a 1.51 MeV proton MEBT. Different values of synchrotron phase with a buncher voltage of 48.4 kV will alter the distribution of longitudinal emittance at the exit of the RFQ.

DEVELOPED BSM IN IMP CAS

The developed BSM based on Feschenko's style is shown in Figure 1. It includes an RF deflector with a 325 MHz half wave resonator (HWR) and double plate-type electrodes. Tunner make sure the resonator frequency working in the differential mode of 325 MHz. The unloaded Q value is about 1923 as shown in Figure 2. The primary beam hits the target wire and produces SE. These electrons are accelerated by a negative voltage of 10 kV applied to the target wire through the first slit to the RF deflector field. The HV focusing is applied to each electrode to centre the electron envelope on the second slit through a high voltage port connected to a 1 MΩ resistance. The corrected magnet is used to control the transverse orbit of the rf-modulated SEs to pass through the energy spectrometer dipole. All SEs with the synchronous phase of the beam are collected with the secondary-electron multiplier, located at the end of the BSM. The signal is amplified through a preamplifier and sampled by a readout electronics.

Firstly, we installed the BSM in a heavy-ion linac called LEAF to test its performance. We conducted five primary measurements of the bunch shape distribution, as illustrated in Figure 3. The phase shift steps were manually adjusted during the measurements. The five measured bunch shape distributions exhibit consistency. The comparison of bunch shape distribution between the rebuncher power turning on and off are shown in Figure 4. The longitudinal distribution disappears when the re-buncher power is turned off, and when the re-buncher power is on, the full width at half maximum (FWHM) of the longitudinal distribution is 16.3° at 81.25 MHz.

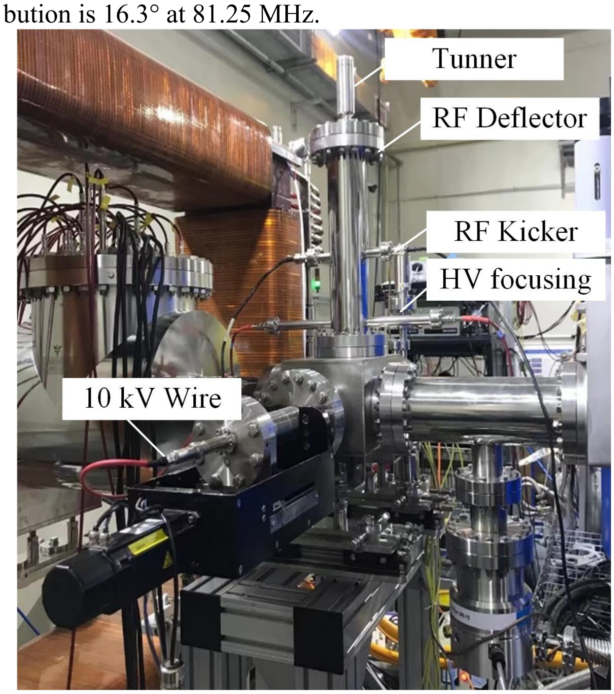

Figure 1: The developed BSM with HWR deflector.

A WASIT-TO-WAIST BEAM TRANSFER LINE AT THE EXIT OF A PROTON RFQ

The setup of longitudinal emittance measurement is shown in Figure. 5, which includes a horizontal slit (Slit2-H) at the input of dipole and the wire of BSM at the output

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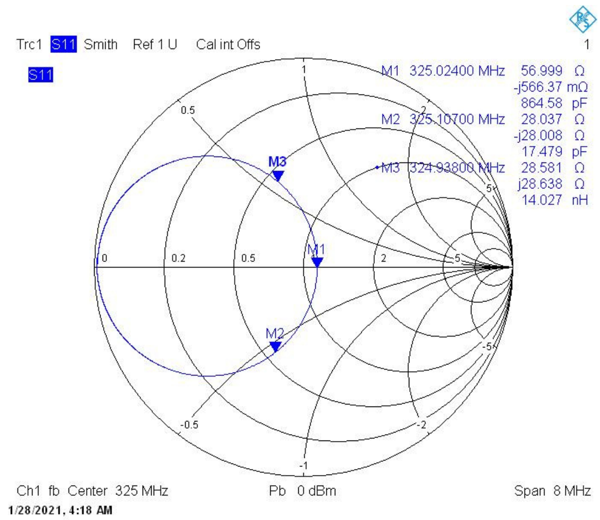

Figure 2: The measured S11 Smith chart for calculating the unloaded Q value of RF-deflector.

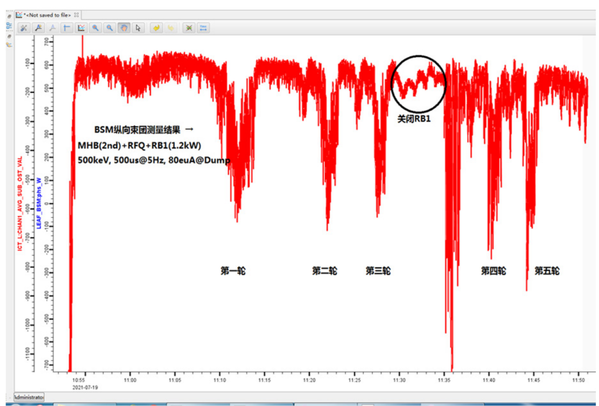

Figure 3: Five measured results of bunch shape distribution.

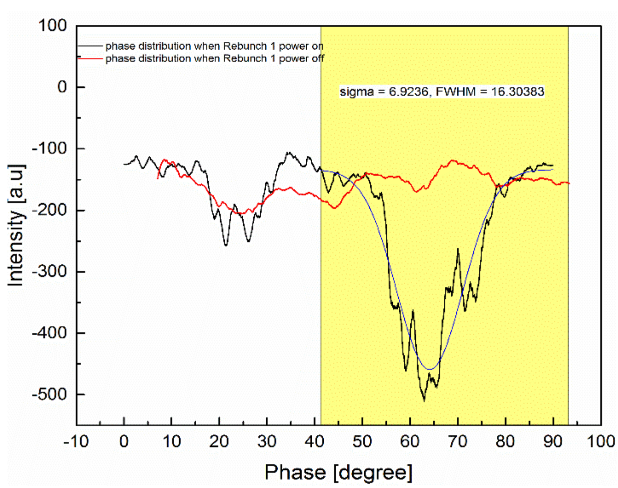

Figure 4: comparison of bunch shape distribution between the rebuncher power turning on and off.

of dipole. In fact, this setup can be used to the six-dimensional phase space measurement if all four slits are installed here. But now there is only one slit named Sli2-H installed here for the longitudinal emittance measurement. The physical parameters of the dipole magnet are as follows: radius ρ = 500 mm, angle φ =90°, edge angles φ_i/φ_e =26.5°/26.5°, peak magnetic field B =0.5 T and gap width = 80 mm. The electrical parameter is the central current I of 314.1 A for the centre energy of 1.52 MeV proton beam. The dipole weight is approximately 835 kg. There is about 1.2 m space before and after the dipole magnet. If a set of horizontal slits (Slit2-H) is placed at the upstream waist of the dipole magnet and a horizontal wire of BSM is placed at the downstream waist, the energy spread distribution at this location can be measured by scanning the dipole magnet current and capturing the signal from the wire of the BSM when it is inserted into the centre of the pipe. The matrix of waist to waist transfer line in MEBT are shown in Figure. 6. The waist-to-waist transfer drift length is 997.171 mm both before and after. The values of M11, M12, and M16 in the matrix are -1, 0, and -2 respectively.

$$\sigma_\beta = M_{11} \cdot x + M_{12} \cdot x' \qquad (1)$$

Eq. (1) shows that σ_β is the transverse profile rms value at the downstream waist position where the BSM wire is located, affected by the transverse emittance. x means the width of the first slit is 0.2 mm. Thus the momentum spread resolution is calculated as

$$\delta = \frac{\Delta p}{p} = \frac{\sigma_\beta}{D} \qquad (2)$$

where σ_β equal to 0.1 mm and D is the value of M16. The momentum spread resolution in the waist to waist lattice is $\delta = \Delta p/p$ =0.1 mm/2 m = 0.01%. Correspondingly, the energy spread resolution is $\Delta w/w$ =0.02%. In this case, the linearity of the dipole magnet current with energy is about 0.005%, and the uniformity of the dipole magnetic field is roughly 0.008%. Considering all factors as mentioned, the energy spread resolution is lower than 0.03%. The waist-to-waist transfer matrix ensures a high-resolution direct measurement of longitudinal emittance in MEBT. When pushing the wire of the BSM inserted in the centre of the beam pipe and sweeping the dipole current in steps of 0.2 A corresponding to an energy step of 967 eV, the current signal from the wire of the BSM could measure the energy spread distribution .The increment of 0.2 A is constrained by the precision of the dipole magnet current control.

DIRECTLY MEASURED LONGITUDIANL EMITTANCE

The entire process of direct longitudinal emittance can be summarized into the following steps. As this is the first time we are measuring the longitudinal emittance directly, we are keeping the RFQ parameters constant to study how the phase of the buncher influence the longitudinal phasespace. Firstly, calibrate the phase and voltage of the buncher in synchrony. Secondly, adjust the steer magnet to keep the beam orbit in the center when the buncher power is on and insert Slit2-H in the center. Thirdly, measure the energy spread distribution to check the scanning range of dipole current in one buncher parameter. Lastly, scan the dipole current and set one dipole current to scan the phase value of BSM and measure the longitudinal bunch length.

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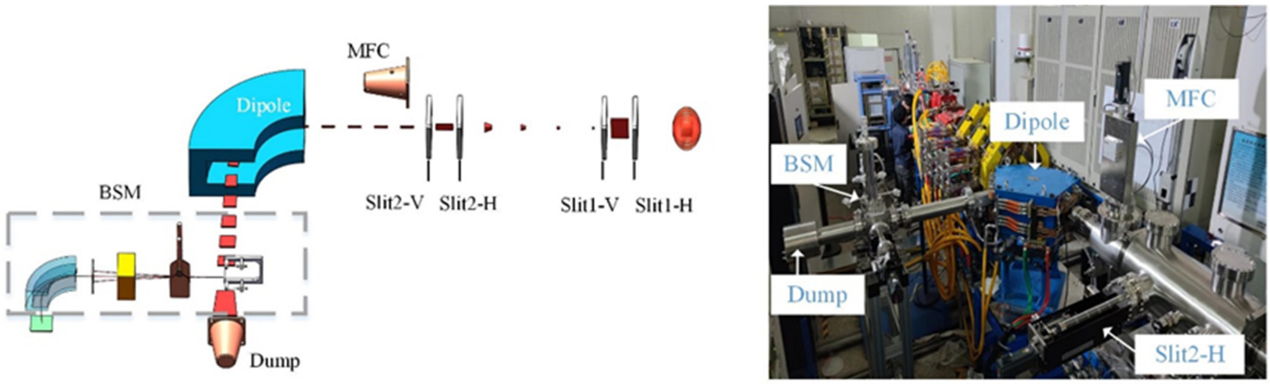

Figure 5: Setup of longitudinal emittance measurement in a waist-to-waist transfer line.

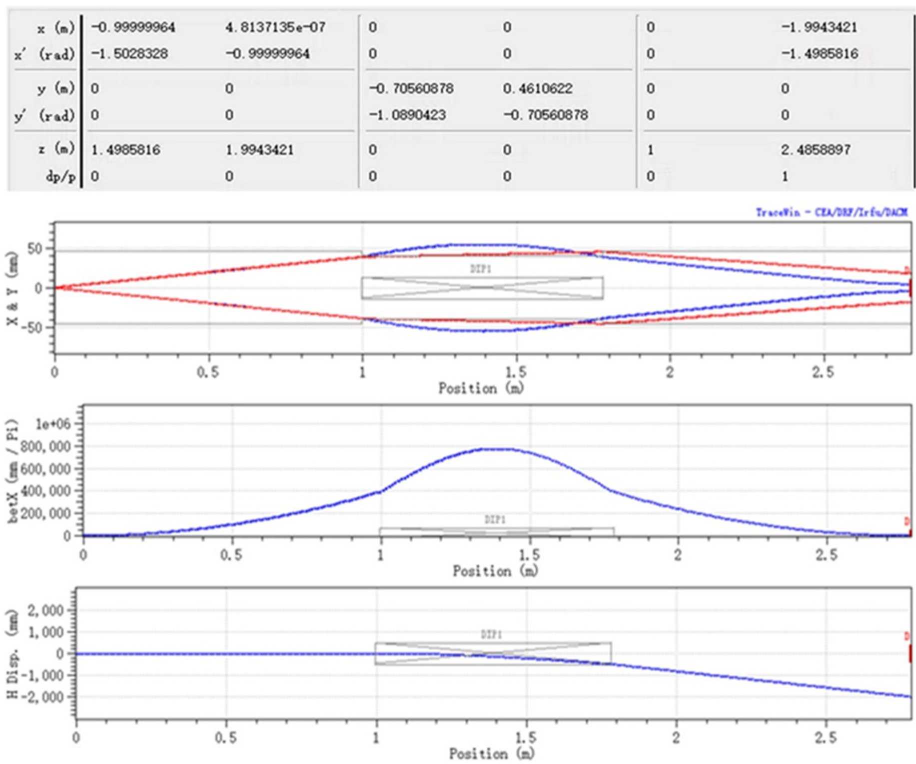

Figure 6: The matrix of waist to waist transfer line in the exit of a proton RFQ with the energy of 1.52 MeV.

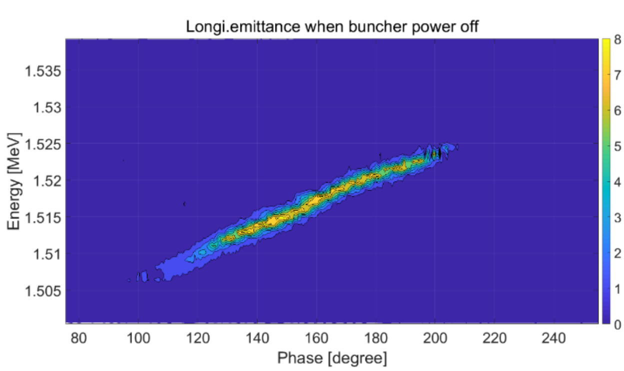

Figure 7: Longitudinal emittance when buncher power off.

When the buncher power was turned off, we conducted the initial longitudinal phase space measurement, as depicted in Figure 7. The central energy of the proton beam was 1.52 MeV with an average current of 300 μA at the RFQ frequency of 162.5 MHz. The pulsed beam had a width of 100 μs and operated at a repetition frequency of 1 Hz. Subsequently, the buncher voltage was adjusted to 48.4 kV, and four longitudinal phase space measurements were carried out while varying the synchronous phase values from -90° to +180°. The measured results are shown in Figure 8. Significant changes in the shape of the longitudinal emittance are observed when buncher tuning off and tuning on to 48.4 kV with the synchrony phase of -90°. Examining the four longitudinal emittance shapes from Figure 8, an anticipated variation is depicted: bunching the beam at the central energy of 1.52 MeV with a synchrony phase of -90°, accelerating the central energy from 1.52 to 1.57 MeV with a synchrony phase of 0°, debunching at the central energy of 1.52 MeV with a synchrony phase of +90°, and deaccelerating the central energy from 1.52 MeV to 1.47 MeV with a synchrony phase of +180°.

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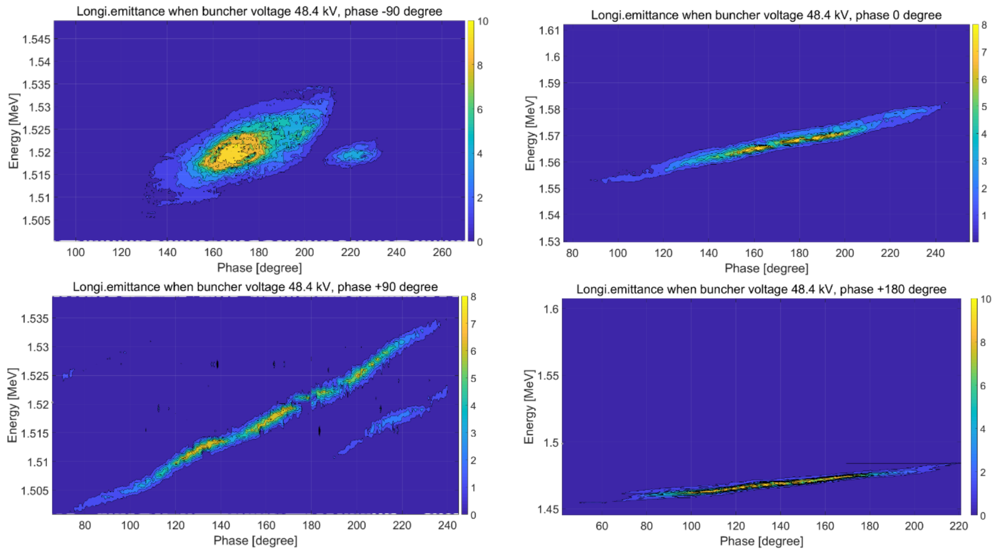

Figure 8: Measured longitudinal emittances (100%) when buncher voltage of 48.4 kV with the synchrony phase of -90°, 0°, +90° and +180°.

Table 1: Measured and Simulated rms Longitudinal Emittance and Twiss Parameters in 5 Buncher Conditions

Buncher paramters	Measured results			Simulated results			ε growth	MF
	ε π.mm.mrad	α ——	β mm/ (π.mrad)	ε π.mm.mrad	α ——	β mm/ (π.mrad)	%	%
Power Off	0.2995	-4.8622	10.7768	0.3709	-2.7287	14.5981	-19	261
-90°	0.8857	-1.0586	1.8946	1.703263	-1.3271	4.5917	173	78
+90°	0.6354	-6.3765	12.1468	0.8074	-6.3386	26.7958	-21	445
0°	0.8994	-3.7317	7.6373	0.3699	-2.7216	14.4216	143	250
+180°	0.7002	-4.0026	10.1502	0.3725	-2.7817	14.5123	88	184

The measured longitudinal emittance and Twiss parameters are listed in Table 1. As the root mean square (rms) parameters can be significantly influenced by the threshold, it is essential to define the threshold applied to the density function of energy and phase [2-3]. Our guiding principle is that the variation in longitudinal emittance should not exceed 5% when subtracting background data exceeding 1%. However, these data do not align with the simulated results. The discrepancy may be due to the initial Twiss parameters from the output RFQ not corresponding to the measured beam. Therefore, the next step would be to conduct a benchmark simulation using the measured longitudinal emittance and Twiss data to refine the theoretical parameters.

CONCLUSION

Five longitudinal emittance measurements were conducted for one buncher power values at four phase degrees, with the buncher power turned off, at the exit of a 1.52 MeV proton RFQ. By adjusting the synchrony phase, the processes of bunching, debunching, acceleration, and deceleration in the longitudinal phase space distributions were directly observed. We utilize a waist-to-waist transfer matrix to enhance the resolution of the energy spread distribution. The impact of transverse emittance on the energy spread is mitigated by a horizontal slit with a width of 0.2 mm. The developed BSM can achieve a resolution smaller than 20 ps compared to the full distribution of 500 ps in the longitudinal direction at 162.5 MHz. Therefore, by enhancing the accuracy of dipole magnet power current control from 0.2 A to 0.01 A, we may be able to reduce the energy spread slice from 1 keV to 50 eV. Directly measuring the longitudinal emittance offers valuable insights into the actual beam phase space distribution. This information can aid in conducting a bench-back simulation using the measured data, rather than relying on the initial distribution from end to end.

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REFERENCES

[1] P. N. Ostroumov, "Development of a medium-energy superconducting heavy-ion linac", *Phys. Rev. Spec. Top. Accel Beams*, vol. 5, p. 030101, 2002. doi:10.1103/PhysRevSTAB.5.030101

[2] G. R. Montoya-Soto *et al*., "Study of longitudinal mechanisms and correlations in the definition of RFQ transverse acceptance", *AIP Advances*, vol. 13, p. 055105, 2023. doi:10.1063/5.0145935

[3] Robert C. Webber, "Longitudinal emittance: An introduction to the concept and survey of measurement techniques including design of a wall current monitor", *AIP Conf. Proc.*, vol. 212, p. 85, 1990. doi:10.1063/1.39712