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EXPERIMENTS ON A BSM TEST BENCH FOR CSNS-II LINAC UPGRADE*

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Abstract

A test bench for commissioning the 324 MHz RF deflectors used in BSMs has been in use for the upgrade project CSNS-II linac. The pulsed 10 keV electron beam produced by a Kimball focusable electron gun has been captured by a YAG:Ce screen and imaged by an industrial camera installed vertically right above the view port of the screen after passing through the body of the RF deflector undertest. This paper introduces the verification experiments of static electric lens, RF deflections and bending magnet, also with the postprocessing of the beam spot images. Results of theoretical analysis and the tests were compared and agreed very well. The experiments verified the feasibility of the BSM test bench, playing a critical role in shortening the future commissioning time of BSM equipment in the tunnel.

INTRODUCTION

The China Spallation Neutron Source (CSNS) comprises an 80 MeV negative hydrogen ion linear accelerator, a 1.6 GeV rapid cycling synchrotron, and a target station [1]. It achieved its design specifications in February 2020, reaching a beam power of 100 kW. In March 2024, the second-phase upgrade project, CSNS-II, was initiated. Table 1 provides a comparative analysis of the parameters between CSNS and CSNS-II [2].

BSM TEST BENCH SETUP

To meet the requirements for measuring the longitudinal density distribution of beam bunches following the upgrade of the linear accelerator in the second phase of the spallation neutron source project, the independent development of the Bunch Shape Monitor (BSM) was initiated [2]. Prior to the installation of the new BSM in the CSNS linear accelerator tunnel, extensive preparatory and testing work in the laboratory was essential. The 324 MHz radiofrequency deflection cavity and the bending magnet used for deflecting the particle beam was designed, fabricated and commissioned [3].

Currently, a complete BSM verification setup has been established in the laboratory. The full optical path has been constructed, and preliminary verification of the BSM principle has been achieved. A wealth of beam spot observation images has been obtained, and extensive analysis has been conducted. These efforts have laid a solid foundation for the practical application of the BSM in the upgraded accelerator system.

Table 1: Main Parameters of CSNS and CSNSII

Project Phase	I	II
Beam Power on target [kW]	100	500
Proton energy [GeV]	1.6	1.6
Average beam current [μA]	62.5	312.5
Pulse repetition rate [Hz]	25	25(+25)
Linac energy [MeV]	80	300
Linac type	DTL	+Spoke+ELL
Linac RF frequency [MHz]	324	324
Macropulse. ave current [mA]	15	50
Macropulse duty factor	1.0	1.7
RCS circumference [m]	228	228
harmonic number	2	2
RCS Acceptance [πmm-mrad]	540	540
Target Material	Tungsten	Tungsten

OPTICAL PATH CALIBRATION AND PREPARATORY WORK

The experimental verification setup for the BSM includes a Kimball EGS4212 electron gun, a 324 MHz radiofrequency deflection cavity prototype, an ion pump system, a six-way vacuum chamber, a dipole magnet, a straight-through optical path fluorescence screen, and an imaging assembly consisting of a Microchannel Plate (MCP), a fluorescence screen, and a Basler camera. During the debugging of the electron beam straight-through optical path, the dipole magnet and the MCP+fluorescence screen+Basler camera imaging assembly are not required, as illustrated in Fig. 1.

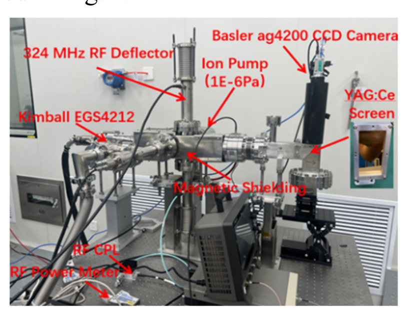

Figure 1: Direct beam optics of the BSM test bench.

During the operation of the electron gun, the parameters are set as follows: V_{source} = 1.2 V, I_{source} = 1.433 A, $I_{emission}$

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= 16 μA, and the camera exposure time is 500 ms. The adjustment of the electron beam path is achieved by fine-tuning the $V_{X\text{-deflection}}$ and $V_{Y\text{-deflection}}$ parameters of the electron gun [4].

The radiofrequency (RF) deflection cavity is the core component of the bunch shape monitor. The cavity typically consists of two deflection electrode plates, RF power input, RF signal pickup, and tuning components. By applying a constant negative DC voltage Vfocus to the electrodes, the secondary electron beam is focused. Additionally, applying DC voltages ±Vsteer generates a transverse deflection force on the electron beam [5]. The working principle is illustrated in Fig. 2.

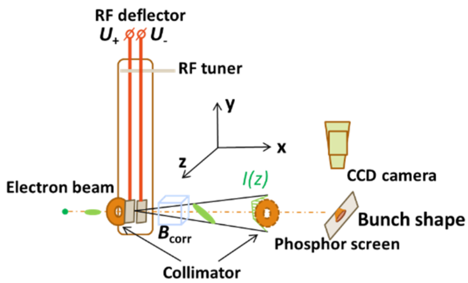

Figure 2: Principle of an RF deflector in BSM.

RELATIONSHIP BETWEEN BEAM SPOT POSITION AND VOLTAGE IN GUN DEFLECTION PLATES AND DEFLECTION PLATES

After preparatory work, the first was to verify the relationship between the beam spot position and the variation in deflection voltage. As shown in Fig. 3, with the deflection voltage in the x-direction (x_{def}) fixed, the deflection voltage in the y-direction (y_{def}) was changed at equal intervals to observe the corresponding changes in the beam spot position. Data fitting revealed that both trends exhibit a linear relationship. Specifically, the calculated rate of change in the x-direction is 0.31 mm/V, and in the y-direction, it is 0.113 mm/V.

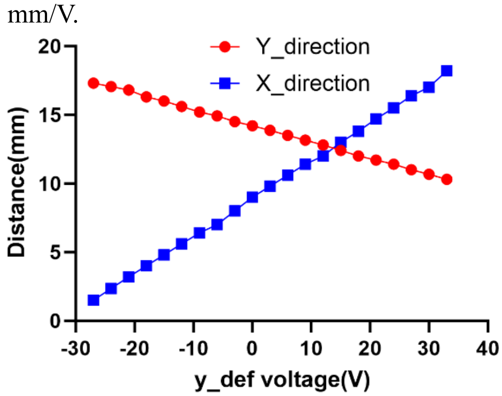

Figure 3: The variation trend of X/Y coordinate values with y_{def} voltage changes.

As shown in Fig. 4, with y_{def} fixed, the x_{def} was changed at equal intervals to observe the corresponding changes in the beam spot position. Data fitting revealed that both trends exhibit a linear relationship. Specifically, the calculated rate of change in the x-direction is 0.126 mm/V, and in the y-direction, it is 0.296 mm/V.

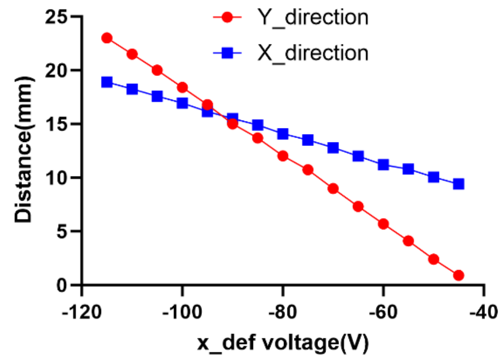

Figure 4: The variation trend of X/Y coordinate values with x_{def} voltage changes.

The CH0 and CH1 outputs of the ISEG DC high-voltage power supply were connected to the two electrode plates of the RFD, and voltages were applied accordingly. By fixing the voltage applied to either CH0 or CH1 and varying the voltage applied to the other channel, the voltage difference between the plates was altered. As shown in Fig. 5, under constant other conditions, the beam spot position changes with the variation in the voltage difference between the plates. Data fitting revealed that the changes in both the x-direction and y-direction exhibit a linear relationship. Specifically, the calculated rate of change in the x-direction is 0.163 mm/V, and in the y-direction, it is 0.022 mm/V.

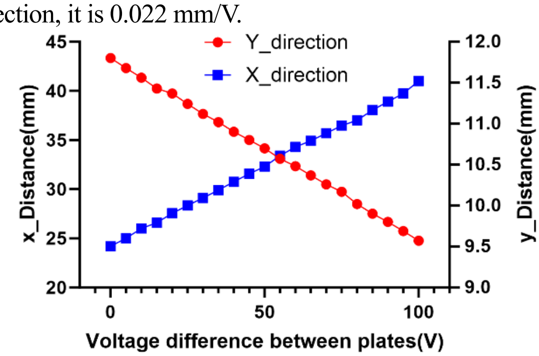

Figure 5：The relationship curve between beam spot position and focusing voltage.

When the voltage difference between the plates exceeds 200 V, the beam spot deviates completely and cannot be displayed on the fluorescence screen.

RELATIONSHIP BETWEEN RF POWER IN THE CAVITY AND BEAM SPOT DISTRIBUTION WIDTH

The external synchronization signal for the RF deflection cavity was set to 1 Hz with a pulse width of 50 ms, while the synchronization signal for the Basler camera was set to 2 Hz. The pulse-modulated 324 MHz RF signal was fed into a 324 MHz RF power amplifier that domestically produces 1 kW power and then introduced into the RF deflection cavity. The RF power inside the cavity was calculated based on readings from RF couplers, attenuators, and power meters connected to

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two ports. The changes in the beam spot distribution width were observed and recorded using the camera.

Adjusting the deflection voltage inside the electron gun, the center of the beam spot was aligned to the center of the fluorescence screen. The output signal amplitude of the RF signal source was gradually increased from -38 dBm to -23 dBm, and the changes in the beam spot were recorded.

Under constant other conditions, as the RF power inside the cavity increased, the horizontal dimension of the beam spot (σx) gradually expanded, while the vertical dimension (σy) remained essentially unchanged, as shown in Fig. 6. This validates the modulation function of the RF deflection cavity on the electron beam in the horizontal direction.

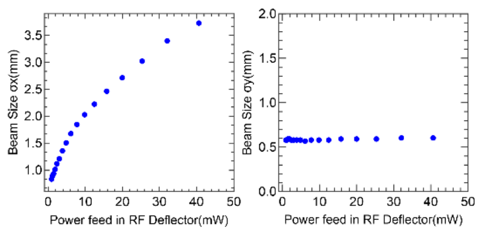

Figure 6: The relationship curve between beam spot width and RF power in the cavity.

MCP+YAG:CESCREEN+ BASLER:CAMERA IMAGING ASSEMBLY

MCPs are widely employed in various high-sensitivity detection and imaging systems. In this experiment, a dual-layer MCP was installed to amplify the electron signal, thereby enhancing the energy of the electron beam and compensating for the energy loss after the electrons pass through the deflection magnet. By varying the excitation current, the movement of the beam spot was observed.

The MCP includes an input electrode, an output electrode, and a fluorescent screen electrode, with applied voltages of 0 V, 1200 V, and 4300 V, respectively. The input electrode is pulled to 0 V potential through an external pull-down resistor.

The camera position was adjusted so that the fluorescence screen could fully appear within the camera's field of view. The diameter of the fluorescence screen is 50 mm, corresponding to 1860 pixels, which yields an imaging resolution of 0.02688 mm/pixel for the camera.

By adjusting the output value of the current source, the magnetic field strength of the deflection magnet was varied. The beam spot was located, and the changes in its distribution position were observed and recorded using a camera. By gradually adjusting the output current of the current source, the beam spot was finally observed when the excitation current was in the range of 3.1–3.17 A. Due to the inherent dispersion of the electron beam emitted from the electron gun, the beam spot appeared elliptical after being acted upon by the deflection magnet, as shown in Fig. 7.

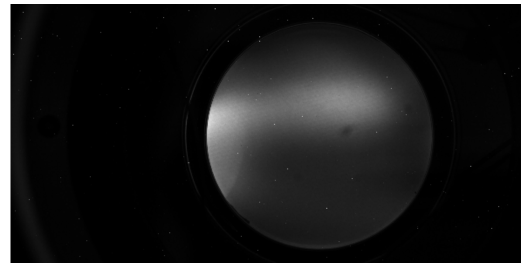

Figure 7: Electron Beam Spot After Interaction with the Deflection Magnet.

Based on the calibration results of the deflection magnet, the corresponding magnetic flux density is determined to be 67.4–68.7 Gs. With the center of the fluorescence screen as the coordinate origin, the horizontal rightward and upward directions of the screen image are defined as the positive directions for the horizontal and vertical coordinates of the beam spot center, respectively. The relationship between the beam spot center position and the deflection magnetic field strength is illustrated in Fig. 8.

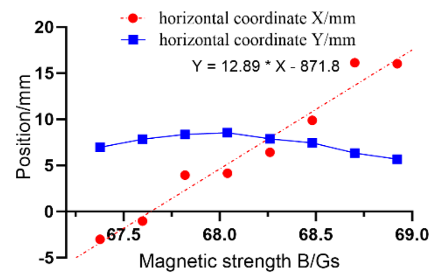

Figure 8: Relationship between the beam spot center position and the deflection magnetic field strength.

CONCLUSION

On the BSM experimental test platform, the optical path setup and a series of experimental studies on the beam spot were completed. The effects of the electron gun bias voltage, RF deflection cavity, deflection magnet, and MCP on the optical path were investigated, validating the feasibility of this BSM setup and providing valuable experience for its formal installation in the future.

In the later stages of the experiment, to more closely simulate the real operational environment inside the accelerator tunnel during beam tuning, a single-wire tungsten target (100 µm in diameter) will be used to generate a thermal electron beam for further experiments and analysis. The single-wire target has already been installed, and the related experiments are scheduled to be completed by the end of 2025.

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