

Long-term beam stability assessment of the CATHL carbon ion pencil beam scanning system for clinical radiotherapy

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Abstract

Carbon ion pencil beam scanning (PBS) therapy offers superior dose conformity and enhanced biological effectiveness for cancer treatment. While several international facilities have reported long-term beam stability data, no comprehensive assessment has been published for the domestically developed CATHL carbon ion therapy system deployed in China. In this study, we present a systematic evaluation of beam delivery performance over an eight-month period (August 2025 to March 2026) at the Zhejiang Cancer Hospital Heavy Ion Medical Center. The assessment encompasses dose output consistency from weekly quality assurance (QA) measurements across 12 beam configurations in two clinical treatment rooms, as well as daily spot position accuracy and beam spot size characterization from 69,382 individual spot measurements across four beam nozzles. Statistical process control (SPC) analysis of dose output revealed a mean deviation of $+0.15\% \pm 0.73\%$ from reference values, with 95.4% of all measurements falling within the $\pm 3\%$ clinical tolerance. Spot position accuracy yielded a mean radial error of 0.53 ± 0.31 mm, with 95.6% of spots within the 1-mm acceptance criterion. Beam spot sizes (σ) ranged from 1.3 to 4.4 mm, consistent with Coulomb scattering physics, and exhibited no systematic temporal drift. Additional beam quality metrics including spot symmetry (skewness $|mean| < 0.008$), 2D roundness ($3.66 \pm 3.92\%$), and amplitude uniformity ($CV < 5\%$) further confirmed robust beam delivery performance. These results demonstrate that the CATHL carbon ion PBS system achieves beam stability comparable to established international facilities, supporting its suitability for clinical radiotherapy applications.

Full Text

Preamble

Long-term beam stability assessment of the CATHL carbon ion pencil beam scanning system for clinical radiotherapy Jia-Hao Wang,¹ An-Kang Hu,² Jian-Xin Ni,³ Xue Bai,¹ Bin-Bing Wang,¹ Ji-Ping Liu,¹ and Guo-Ping Shan¹, *

Zhejiang Cancer Hospital, Hangzhou Institute of Medicine (HIM), Chinese Academy of Sciences, Hangzhou, Zhejiang 310022, China Ruijin Hospital, Shanghai Jiao Tong University School of Medicine, Shanghai 200025, China Lanzhou KeJinTaiji New Technology Co., Ltd, Lanzhou, Gansu 730000, China Carbon ion pencil beam scanning (PBS) therapy offers superior dose conformity and enhanced biological effectiveness for cancer treatment. While several international facilities have reported long-term beam stability data, no comprehensive assessment has been published for the domestically developed CATHL carbon ion therapy system deployed in China. In this study, we present a systematic evaluation of beam delivery performance over an eight-month period (August 2025 to March 2026) at the Zhejiang Cancer Hospital Heavy Ion Medical Center. The assessment encompasses dose output consistency from weekly quality assurance (QA) measurements across 12 beam configurations in two clinical treatment rooms, as well as daily spot position accuracy and beam spot size characterization from 69,382 individual spot measurements across four beam nozzles. Statistical process control (SPC) analysis of dose output revealed a mean deviation of $+0.16\% \pm 1.59\%$ from reference values, with 95.6% of all measurements falling within the $\pm 3\%$ clinical tolerance. Spot position accuracy yielded a mean radial error of 0.53 ± 0.31 mm, with 95.6% of spots within the 1 mm acceptance criterion. Beam spot sizes (σ) ranged from 1.3 to 4.4 mm, consistent with Coulomb scattering physics, and exhibited no systematic temporal drift. Additional beam quality metrics including spot symmetry (skewness $|\text{mean}| < 0.008$), 2D roundness ($3.66 \pm 3.92\%$), and amplitude uniformity ($\text{CV} < 5\%$) further confirmed robust beam delivery performance. These results demonstrate that the CATHL carbon ion PBS system achieves beam stability comparable to established international facilities, supporting its suitability for clinical radiotherapy applications.

Keywords

Carbon ion therapy, Pencil beam scanning, Beam stability, Quality assurance, Statistical process control, CATHL

INTRODUCTION

strating spot position accuracy within 0.5 mm and dose reproducibility within 2% [6]. Mirandola et al. presented the 30 dosimetric commissioning and quality assurance results of 31 the CNAO facility in Pavia, Italy, reporting dose output con32 stancy within $\pm 3\%$ and beam position accuracy better than 33 1 mm [8].

Tessonnier et al. and Shirai et al. have additionally contributed performance benchmarks from HIT (Heidelberg) [10, 11] and HIMAC [13], respectively. These publications collectively establish the international standards against which new carbon ion therapy systems should be evaluated.

In China, the development of indigenous carbon ion therapy technology has accelerated significantly in the past 40 years. The Carbon Ion Therapy System for Human Cancer Treatment in Lanzhou (CATHL) was developed by the Institute of Modern Physics (IMP), Chinese Academy of Sciences, building on decades of heavy-ion physics research, and is commercially manufactured by Lanzhou KeJinTaiji New Technology Co., Ltd. (also known as Lanzhou KeJinTaiji or CATHL Technology) [15, 16]. Multiple CATHL systems are now installed or under construction at hospitals across China, representing the first domestically developed carbon ion therapy platform to enter widespread clinical use. The Zhejiang Cancer Hospital located in Hangzhou, began clinical treatments in February 2025 and has since treated over 660 patients with head and neck, thoracic, abdominal, and pelvic tumors.

Despite this rapid clinical deployment, no peer-reviewed publication has systematically characterized the long-term beam delivery performance of the CATHL system. Such data are urgently needed for several reasons: (1) to demonstrate that the domestically developed system meets the beam stability standards established by international facilities; (2) to pro-

Carbon ion radiotherapy has emerged as a promising treatment modality for radioresistant tumors, offering a unique combination of physical and biological advantages over conventional photon therapy [1-3].

The characteristic Bragg peak of carbon ion beams enables sharp dose localization at depth, while the elevated linear energy transfer (LET) in the Bragg peak region results in enhanced relative biological effectiveness (RBE), making carbon ions particularly effective against hypoxic and photon-resistant tumor cells [1].

Pencil beam scanning (PBS) is the state-of-the-art beam delivery technique for carbon ion therapy, in which individual beam spots of sub-centimeter diameter are magnetically steered across the target volume in three dimensions [4, 5]. Compared to passive scattering methods, PBS enables superior dose conformity and reduces neutron contamination, but places more stringent demands on beam delivery accuracy and stability. The clinical safety and efficacy of PBS treatments critically depend on the long-term reproducibility of several beam parameters, including absolute dose output, spot position accuracy, beam spot size, and spot intensity uniformity [6, 8].

Recognizing this importance, several international carbon ion therapy centers have published comprehensive beam performance data. Furukawa et al. reported on the performance of the fast scanning system at the National Institute of Radiological Sciences (NIRS, now QST) in Chiba, Japan, demon-

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B. Quality assurance program provide a reference dataset for the growing number of CATHL 111 installations in China; (3) to contribute to the global body of knowledge on carbon ion beam characteristics; and (4) to The institutional QA program follows the general recommendations of AAPM Task Group reports and IAEA protocols to inform clinical protocols and quality assurance procedures. 114 protocols adapted for carbon ion PBS therapy.

Recent developments In this work, we present a comprehensive assessment of 115 components in beam monitoring instrumentation for heavy-ion 66 beam delivery stability at the Zhejiang Cancer Hospital covering 116 facilities have been reported in the literature [19, 20]. Two 67 during an eight-month period from August 2025 to March 2026. 117 complementary QA procedures were analyzed in this study: 68 The study encompasses dose output monitoring using statistical 118 weekly dose output verification and daily spot position/beam 69 statistical process control (SPC) methodology, spot position accuracy 119 size QA. 70 accuracy evaluation based on a 49-spot grid protocol, beam 71 spot size characterization across the full clinical energy range

1. Weekly dose output monitoring

72 (120–400 MeV/u), and analysis of supplementary beam quality 120 73 its metrics including skewness, 2D roundness, and amplitude 74 uniformity.

Absolute dose output constancy was verified weekly using a plane-parallel ionization chamber (PTW Markus 34045, 123 PTW Freiburg, Germany) with a calibration factor $K_{\text{user}} = 1.004$. The chamber was positioned at the isocenter within a 125 solid water phantom at a depth of 100 mm water-equivalent, II. MATERIALS AND METHODS 126 corresponding to the mid-range of clinically used depths.

For each of the four beam nozzles, three representative A. Treatment facility and accelerator system 128 beam energies were selected for monitoring, corresponding 129 to water-equivalent depths of approximately 100 mm (low 130 energy), 150 mm (mid energy), and 200 mm (high energy).

The Zhejiang Cancer Hospital Heavy Ion Medical Center 131 This yields 12 beam configurations in total (4 nozzles \times 3 energies): R2-H-100, R2-H-150, R2-H-200, R2-V-100, R2-V-150, R2-V-200, R3-H-100, R3-H-150, R3-H-200, R3-O-100, R3-O-150, R3-O-200. Standard verification plans specify 134 R3-O-150, and R3-O-200. Standard verification plans specify 135 beam ions, a compact cyclotron serving as the injector, and a 135 specific to each configuration were delivered, and the measured 126+ 82 synchrotron ring that accelerates C ions to the clinical 136 dose was compared against a baseline reference value established 83 energy range.

The system employs the pencil beam scan technique during initial commissioning. The percentage deviation technique for dose delivery, with 123 discrete energy steps spanning 120.26 to 399.92 MeV/u. These energies correspond to water-equivalent penetration depths of approximately 30 to 270 mm, covering the full range of clinically relevant target depths for carbon ion therapy.

Beam energy switching is performed via the synchrotron extraction energy, while lateral beam steering is achieved using

2. Daily spot position and beam size QA

Using a pair of orthogonal scanning magnets located in each treatment nozzle. The beam intensity is controlled through Spot position accuracy and beam spot characteristics. The combination of ECR source output, injection efficiency, were assessed daily prior to clinical treatments using an IBA myQA Phoenix digital detector array (IBA Dosimetry, planning system (TPS) used at our center is the PHOENIX Schwarzenbruck, Germany). The Phoenix detector was positioned at the isocenter and aligned using the room laser coordinate

The facility comprises four treatment rooms arranged in a circular system, as shown in Fig. 2 [Figure 2: see original paper]. around the synchrotron and beam transport system. During a standardized 49-spot grid measurement protocol was used the study period (August 2025 to March 2026), Room 2 and Room 3 were in routine clinical operation, Room 1 was under commissioning, and Room 4 was pending equipment installation. Room 2 is equipped with two beam nozzles delivered with 5000 monitor units (MU) to ensure adequate signal-to-noise ratio.

To ensure comprehensive coverage of the full clinical energy range within a practical measurement time, a systematic energy rotation protocol was implemented. The available energies were divided into five equally spaced energy bands (low, mid-low, mid, mid-high, and high), and one horizontal band. A schematic layout of the accelerator energy from each band was measured per session, yielding five energies per day. The specific energies advanced sequentially through the complex and beam transport system

is shown in Fig. 1 [Figure 1: see original paper].

ion source, a compact cyclotron injector, and a synchrotron. The beam transport system delivers 12 C^{6+} ions to four treatment rooms, of which Rooms 2 and 3 were in clinical operation during the study period.

widths (σ_{major} , σ_{minor}), rotation angle (θ), and a roundness metric.

The clinical acceptance criterion for spot position accuracy was $r < 1.0\text{ mm}$ (radial deviation from nominal). Spots exceeding this threshold triggered investigation and potential recalibration of the scanning magnet deflection coefficients (K-values).

The 49-spot grid QA protocol was implemented in August 2025. Prior to this date, a single central spot measurement was performed daily under a different protocol; these earlier data are excluded from the present analysis due to the different measurement geometry.

The IBA myQA Phoenix digital detector array is positioned at the isocenter and aligned using the room laser system.

Statistical analysis methods

Dose output: Statistical process control

each day, such that all 123 energies were measured over approximately 25 working days. This rotational approach ensures that every clinical energy is periodically sampled using Shewhart control charts, a standard statistical process control technique widely used in industrial quality management. Spot analysis was performed using the IBA myQA software platform (Multiple Spot Analysis module) with the following analysis parameters: Gaussian cut intensity threshold (μ), standard deviation (σ), and upper/lower control limits of 5% (minimum signal level for inclusion in the fit), (UCL/LCL = $\mu \pm 3\sigma$) were computed from the full dataset. Peak identification threshold of 80% (relative to the maximum pixel intensity), neighbor consideration radius of 10 pixels control (OOC) events.

Two data points in Room 3 (one in R3-H-150 and one for peak separation, and a maximum of 1000 iterations for the Gaussian fitting algorithm. For each detected spot, both in R3-H-200) exhibited deviations exceeding -49% , which one-dimensional Gaussian fits (independent X and Y projections) were clearly inconsistent with all surrounding measurements and a two-dimensional rotated elliptical Gaussian fit was attributed to data entry errors in the recording were performed.

The 1D fits yield spot centroid position, sheet. These two outliers were excluded from statistical analysis standard deviation (σ_X , σ_Y), skewness, and

peak amplitude. 207 ysis. The institutional clinical tolerance for dose output deviation is $\pm 3\%$. The 2D fit additionally provides the major and minor axis deviation, which was set at $\pm 3\%$.

Spot position accuracy metrics

RESULTS

A. Dose output stability For each measured spot, the position deviation was computed by comparing the 1D Gaussian fit centroid to the nominal grid position. Given the grid spacing of 25 mm, a total of 594 weekly dose output measurements were collected and the expected deviations on the order of 1 mm, the nearest-neighbor assignment is unambiguous. The radial position error from April 2025 to March 2026 (approximately 50 measurement sessions per beam). Figure 3 [Figure 3: see original paper] presents the SPC control charts for all 12 configurations arranged in a 4×3 grid $r = (\Delta X)^2 + (\Delta Y)^2$ (1) (4 nozzle groups \times 3 energies), and Table 1 summarizes the key statistical parameters. 217 where $\Delta X = X_{\text{meas}} - X_{\text{nom}}$ and $\Delta Y = Y_{\text{meas}} - Y_{\text{nom}}$. The overall mean dose deviation across all configurations Summary statistics computed include the mean radial error and measurements was $+0.15\%$ with a pooled standard deviation ($\bar{\sigma}$), standard deviation (σ), 95th percentile (r_{95}), and the percentage of spots within the 1.0 mm acceptance criterion. 265 tion was 1.42% .

The mean within-beam standard deviation of spots within the 1.0 mm acceptance criterion. 265 tion was 1.42% .

Among the 12 individual beam configurations, mean deviations ranged from -1.89% (R3-O-150) to $+0.93\%$ (R3-H-200), indicating a slight systematic positive bias for most configurations and a negative offset for the

3. Beam spot size characterization

oblique nozzle at mid-energy. Of all 594 measurements, 95.6% fell within the $\pm 3\%$ clinical tolerance, and 79.1% were within $\pm 2\%$ of the one-dimensional Gaussian fit in the X direction. The relationship to the full width at half maximum (FWHM) commonly used in the literature is $\text{FWHM} = 2.355\sigma$. The energy dependence of spot size was analyzed throughout the monitoring period. 227 by plotting the mean σ versus beam energy for each nozzle.

Room 3 beam configurations generally exhibited tighter Temporal stability was assessed through time-series plots of distributions (SD = 1.15–1.37%) compared to Room 2 (SD = 229 daily σ values, stratified by energy

range (low: < 200 MeV/u; 278 1.34-2.01%), with Room 2 Vertical showing the largest variability (279 2.01%). This difference may reflect the different beam transport geometries or the effects of gravitational loading on the vertical nozzle components.

Supplementary beam quality metrics

Three additional metrics were analyzed to provide a comprehensive characterization of beam spot quality: (1) Skewness (S_1): the third standardized moment of the 1D beam intensity profile, defined as $S_1 = E[(x - \mu)^3] / \sigma^3$. A value of zero indicates perfect Gaussian symmetry; positive values indicate a right-skewed tail and negative values a left-skewed tail. Clinically, non-zero skewness could indicate beam halo effects or scanning magnet nonlinearities. (2) Roundness (R2D): derived from the 2D elliptical Gaussian fit as the relative difference between the major and minor axis standard deviations:

$$R2D = \frac{|\sigma_{major} - \sigma_{minor}|}{(\sigma_{major} + \sigma_{minor})/2} \times 100\%$$

Configuration	n	Mean	SD	Range	OOC
Room 2, Horizontal (90°)	52	+0.47	1.64	R2-H-100	53
Room 2, Vertical (0°)	51	+0.75	2.02	R2-V-100	51
Room 3, Horizontal (90°)	47	+0.74	1.25	R3-H-100	47
Room 3, Oblique (45°)	49	+0.29	1.12	R3-O-100	49

A value of 0% indicates a perfectly circular beam spot; larger values indicate increasing ellipticity. (3) Amplitude coefficient of variation (CV): the ratio of the standard deviation to the mean of the peak amplitudes across all 49 spots in a single measurement, expressed as a percentage. This metric quantifies the uniformity of the delivered spot intensity across the scanning field and is sensitive to beam intensity modulation stability and monitor chamber response variations. $\mu = +0.15\%$ and $\sigma = 1.59\%$. Figure 4b [Figure 4: see original paper] presents a per-beam boxplot

3 energy levels). Black horizontal lines: process mean; red dashed lines: $\pm 3\sigma$ control limits; green-shaded bands: $\pm 3\%$ clinical tolerance.

Room 2 configurations are shown in blue tones (top two rows); Room 3 in warm tones (bottom two rows).

Figure 4b illustrates the consistent performance across most configurations at 0.5 mm and 1.0 mm radii. Table 2 summarizes configurations and the slightly

negative offset of R3-O-150. 294 the position accuracy statistics per nozzle and overall.

The overall mean radial position error was $\bar{r} = 0.53 \pm 0.31$ mm, with the 95th percentile at $r_{95} = 0.98$ mm and B. Spot position accuracy 297 the 99th percentile at $r_{99} = 1.25$ mm. A total of 95.6% of 298 all spots fell within the 1.0 mm acceptance criterion. The A total of 69,382 individual spot position measurements 299 mean systematic offsets were $\Delta X = -0.19$ mm and $\Delta Y = 0.289$ mm were analyzed from 149 measurement days across the four 300 $+0.32$ mm, indicating a small but consistent bias.

Among the four nozzles, R3O (45°) demonstrated the best 290 beam nozzles during the period August 2025 to March 2026. 301 291 Figure 5 [Figure 5: see original paper] displays two-dimensional scatter plots of position 302 performance with 98.6% of spots within 1 mm and the small 292 deviations (ΔX , ΔY) for each nozzle, with concentric refer- 303 est r_{95} of 0.92 mm, while R3H (90°) exhibited the largest

of dose deviations by beam configuration, grouped and color-coded by treatment room and nozzle.

deviations (92.6% within 1 mm, $r_{95} = 1.12$ mm). The two 325 FWHM values range from approximately 3.1 mm to 10.4 mm Room 2 nozzles performed similarly, with approximately 93-326 across the full energy range. 306 94% of spots within 1 mm.

All four nozzles showed highly consistent σ -versus-energy The radial deviation distribution (Fig. 6a [Figure 6: see original paper]) shows a 328 curves (Fig. 6b), confirming that the beam optics design and 308 Rayleigh-like shape with a long tail extending to approxi- 329 magnet calibration are uniform across treatment rooms and 309 mately 2 mm. The distributions for all four nozzles overlap 330 nozzle orientations. The overall mean σX across all energies 310 substantially, with R3H showing a slightly broader tail. 331 and nozzles was 2.24 ± 0.63 mm. 333 the eight-month monitoring period. Each panel corresponds centile. 336 observed for any nozzle, indicating stable beam optics perNozzle Days Spots ΔX ΔY $\bar{r} \pm \sigma r_{95} < 1$ mm 337 formance throughout the study period despite multiple main(mm) (mm) (mm) (mm) 338 tenance interventions on the accelerator and beam transport 74 18,200 $-0.21 + 0.19$ 0.48 ± 0.25 0.90 339 systems.

67 16,161 $-0.15 + 0.41$ 0.54 ± 0.277317 , 614 $- 0.23 + 0.220.47 \pm 0.237217$, 407 $- 0.24 + 0.480.63 \pm 0.4314969$, 382 $- 0.21 + 0.330.53 \pm 0.31$

Supplementary beam quality metrics

343 beyond position and size.

Beam spot size

Beam spot size (σX) ranged from approximately 1.3 mm

beam axis is 376 smaller spot size at higher energies further concentrates the 366 aligned with one of the detector's principal planes, minimiz- 377 signal. No temporal trends in amplitude uniformity were ob367 ing this projection effect. The 95th percentile roundness was 378 served, confirming stable beam intensity modulation through356

(dashed), and 1 mm tolerance (dotted red). (b) Beam spot size (σ_X) as a function of beam energy for each nozzle, showing the expected inverse relationship due to Coulomb multiple scattering.

out the monitoring period.

Spot position accuracy

The spot position accuracy achieved in this study ($\bar{r} = 0.53$ mm, $r_{95} = 0.98$ mm, 95.6% within 1 mm) meets This study presents the first comprehensive long-term 411 the clinical requirements for carbon ion PBS therapy. At 412 CNAO, Mirandola et al. reported lateral position accuracy of 382 beam stability assessment of the CATHL domestically devel413 $\sigma < 0.5$ mm at the isocenter [8], comparable to our results. 383 oped carbon ion PBS system in clinical operation. The re414 At NIRS, Furukawa et al. achieved position accuracy within 384 sults provide essential performance benchmarks for this sys415 0.5 mm for the scanning system [6]. The somewhat larger 385 tem and enable direct comparison with established interna416 95th percentile in our study (0.98 mm, just above the 1 mm 386 tional facilities. 417 threshold) suggests that approximately 4% of spots exhibit 418 deviations between 1 and 2 mm, which warrants continued 419 monitoring and potential investigation of contributing factors.

DISCUSSION

Dose output: comparison with international facilities

It is important to note that the data reported from internaThe dose output stability observed in this study (overall 421 tional facilities and those presented in this study differ fun389 mean deviation +0.15%, per-beam SD 1.59%, 95.4% within 422 damentally in nature.

The position accuracy figures from 390 $\pm 3\%$) compares favorably with reports from established car- 423 HIMAC (< 0.5 mm) and HIT (< 1 mm) are system de391 bon ion therapy centers. At CNAO, Mirandola et al. reported 424 sign specifications or commissioning-phase verification re392 dose output reproducibility within $\pm 3\%$ (< 0.5 mm) were derived 394 strated dose reproducibility within $\pm 2\%$ for the HIMAC fast 427 from EBT3 film measurements during the commissioning pe395 scanning system [6, 7].

The slightly larger variability ob- 428 rioid [8]. In contrast, the present study reports long-term rou396 served in our study for certain beam configurations (e.g., 429 tine QA statistics encompassing 69,382 individual spot mea397 R2-V-100 with SD = 2.01%) may reflect the specific chal- 430 surements collected over 149

clinical operating days, incorporating all real-world factors including daily detector setup variations, environmental chamber positioning may introduce additional variability. The SPC analysis demonstrated that the dose delivery best of our knowledge, no comparable large-scale, long-term remained in a state of statistical control throughout the spot position accuracy dataset from daily clinical QA has 11-month monitoring period, with only 2 of 594 measurements exceeding the 3σ control limits. This is a key strength of the present work, as it provides a false alarm rate of 0.27% for a normally distributed process, confirming that no assignable causes of fine clinical operating conditions rather than under optimized commissioning scenarios. Variation were undetected.

energy measured on a given day, color-coded by energy range (red: low, orange: mid, blue: high). Black horizontal lines indicate the overall mean. (a) R2V, (b) R2H, (c) R3O, (d) R3H.

the offset was stable over the entire monitoring period; (2) it was consistent across different beam energies for a given nozzle; (3) the offset magnitude is within the typical alignment A small but consistent systematic offset was observed across all nozzles ($\Delta X = -0.2$ mm, $\Delta Y = +0.2$ to $+0.5$ mm). Systematic offsets of this magnitude are commonly reported in particle therapy QA programs and are accounted for in the scanning misalignment between the Phoenix detector position and the magnet calibration procedure. room laser coordinate system, rather than a true beam delivery error. Several observations support this interpretation:

(1) Systematic position offset

red line indicating the overall mean. (b) Distribution of 2D Gaussian fit roundness (%), showing the larger values for the oblique nozzle (R3O). (c) Mean spot amplitude as a function of beam energy for each nozzle.

Nozzle-specific performance differences

Robustness to maintenance events

Among the four nozzles, R3H (90°, Room 3) showed the largest spot position variability ($\bar{r} = 0.63$ mm, only 92.6% within 1 mm).

This may be related to the longer beam rod, including integrated strip detector replacements (January, February, and June 2025), cyclotron RF

system repairs 459 transport path from the synchrotron to Room 3 compared to 491 (September 2025), replacement of the γ ionization chamber 460 Room 2, which could amplify small instabilities in the beam 461 steering.

Additionally, differences in the scanning magnet 492 in Room 2 (October 2025), and vacuum window replace493 ments (November 2025). Despite these interventions—some 462 calibration history or the local magnetic field environment 494 of which involved critical beam monitoring components—463 may contribute. 495 the SPC analysis showed that beam parameters returned to The oblique nozzle R30 (45°) exhibited the best position 496 within control limits following each maintenance event. Only 465 accuracy ($\bar{r} = 0.47$ mm, 98.6% within 1 mm) but the largest 497 3 of 594 dose measurements exceeded the 3σ limits, and no 466 2D roundness values (6.16%). As discussed above, the ele498 sustained shifts in beam performance were detected. 467 vated roundness is a geometric projection artifact rather than 499 demonstrates the effectiveness of the post-maintenance beam 468 a beam quality issue. When the roundness is corrected for the 500 verification and recalibration procedures at our institution. 469 45 incidence angle (by a factor of $1/\cos(45^\circ)$ in one direc470 tion), the intrinsic beam circularity is comparable to the other 471 nozzles.

G. Clinical implications

The beam stability data presented here have direct implications for clinical practice. The dose output reproducibil504 ity ($\pm 1.59\%$ SD) is well within the overall dose delivery un472 E. Beam spot size and energy dependence 505 certainty budget for carbon ion therapy, which typically al506 lows for $\pm 3\text{--}5\%$ total uncertainty. The spot position accuracy The observed σ -energy relationship (1.3-4.4 mm for 120-507 (95.6% within 1 mm) supports the clinical use of PTV mar508 gins in the range of 2-3 mm, consistent with current practice 474 400 MeV/u) is consistent with theoretical predictions based 475 on Coulomb scattering of C ions in air and the nozzle exit 509 at our institution. The stable beam spot sizes confirm that the 510 treatment planning beam model remains valid over the study 476 window material. The spot sizes are also consistent with val511 period without requiring recalibration. 477 ues reported from other carbon ion facilities operating with 478 similar nozzle designs [6, 8].

Advanced beam monitoring 479 technologies, including pixel sensor-based detectors [18, 21] H. Limitations and future work 480 and novel ionization chamber designs for high dose rate appli481 cations [22], are being actively developed to further improve Several limitations should be acknowledged. First, the 482 beam characterization capabilities for carbon ion therapy sys- 513 483 tems. The absence of temporal drift in spot size over eight 514 daily spot QA data span eight months (August 2025 to March 484 months confirms stable beam optics and magnet power sup- 515 2026); longer-term monitoring is needed to assess seasonal 485 ply performance. 516 effects and multi-year trends.

Second, the position accu502

racy analysis relies on comparison to nominal grid points; a 552 across 69,382

spot measurements was 0.53 ± 0.31 mm, with dedicated gold-standard reference measurement (e.g., using 553 95.6% of spots within the 1.0 mm acceptance criterion and a 519 a high-precision film or silicon strip detector) would provide 554 95th percentile of 0.98 mm. 520 more rigorous position verification. Third, this study charac- 555 (3) Beam spot size: σ ranged from 1.3 to 4.4 mm across 521 terizes beam parameters measured at the isocenter in air and 556 the 120-400 MeV/u energy range, consistent with Coulomb 522 does not directly evaluate dose delivery accuracy within the 557 scattering expectations, and showed no temporal drift. 523 patient geometry, where tissue heterogeneities and range un558 (4) Beam quality: near-perfect Gaussian symmetry (skew524 certainties introduce additional factors. 559 ness < 0.01), spot circularity (R2D = 3.66%), and uniform Future work will focus on: (1) extending the monitor- 560 amplitude (CV $< 5\%$) were maintained throughout the mon526 ing period to multiple years; (2) incorporating treatment log 561 itoring period. 527 file analysis to characterize beam performance during actual These performance metrics are comparable to those re528 patient treatments, including extraction spill structure, real563 ported by established international carbon ion therapy facili529 time position feedback, and delivered MU verification; (3) 564 ties, confirming that the domestically developed CATHL sys530 performing patient-specific QA measurements to bridge the 565 tem meets the beam stability requirements for safe and ef531 gap between machine QA and clinical dose accuracy; and 566 fective pencil beam scanning carbon ion radiotherapy. This 532 (4) comparing performance across multiple CATHL instal567 study provides a valuable reference dataset for the growing 533 lations at different Chinese institutions, which could inform 568 number of CATHL installations in China and contributes to 534 the development of standardized QA protocols for domestic 569 the international knowledge base on carbon ion beam charac535 carbon ion therapy systems. The ongoing development of su570 teristics. 536 perconducting rotating gantries [12] and advanced beam de571 DATA AVAILABILITY 537 livery technologies will also necessitate updated QA method538 ologies.

The datasets generated and analyzed during this study are 573 available in the Science Data Bank repository at [https:// V. CONCLUSIONS 574 www.scidb.cn/en/s/ieENnu](https://www.scidb.cn/en/s/ieENnu).

We have presented the first comprehensive long-term beam stability assessment of the CATHL domestically developed

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542 carbon ion pencil beam scanning therapy system, based on 543 data collected over eight months at the Zhejiang Cancer HosThis work was supported by the Zhejiang Provin544 pital across two clinical treatment rooms and four beam noz- 576 577 cial Natural Science Foundation of China (Grant No. 545 zles. The principal findings are: (1) Dose output stability: the overall mean deviation from 578 LTGY24A050001). The authors gratefully acknowledge the 547 reference was $+0.15\%$ with a per-beam standard deviation of 579 medical

physics team of the Zhejiang Cancer Hospital Heavy 548 1.59%, and 95.4% of 594 weekly measurements fell within 580 Ion Medical Center for their dedicated daily QA measure549 the $\pm 3\%$ statistical control limits. (2) Spot position accuracy: the mean radial position error 583 mentation and maintenance records.

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