G. Liu, *et al*.: X-Ray Calibration of Dee Voltage of Radiofrequency Cavity Based ...
Nuclear Technology & Radiation Protection: Year 2019, Vol. 34, No. 3, pp. 249-255

249

X-RAY CALIBRATION OF DEE VOLTAGE OF RADIOFREQUENCY CAVITY BASED ON A LOW-POWER TEST

by

Guang LIU [1,2], *Yuntao SONG* [1,2], *Gen CHEN* [1*], *Yanping ZHAO* [1], *Antonio CARUSO* [3], *Luciano CALABRETTA* [3], *and Xin ZHANG* [1]

[1]Institute of Plasma Physics, Chinese Academy of Sciences, Hefei, China
[2] University of Science and Technology of China, Hefei, China
[3] Southern National Laboratory, Catania, Italy

Radiofrequency cavity is one of the most critical and complicated components in a cyclotron. Dee voltage of radiofrequency cavity accelerates charged particles to achieve required energy. Peak voltage of Dee is the key parameter of an radiofrequency cavity. Balanced Dee voltage is very important for effective beam cantering and beam extracting. An X-ray measurement has been made to calibrate and verify the peak voltage of Dee in a low-power (20 kW) test. The X-ray measurement for radiofrequency cavity was designed by means of bremsstrahlung. A suitable shielding cover was chosen for radiofrequency cavity and the X-ray measurement design was demonstrated according to the theory of photon transmission. Finally, the peak voltage of Dee was obtained at the power of 10-20 kW and the balance of Dee voltage was verified.

Key words: cyclotron, radiofrequency cavity, Dee voltage, bremsstrahlung, low-power test

INTRODUCTION

The SC200 cyclotron is a compact superconducting particle accelerator mainly used in proton therapy. Radiofrequency (RF) cavity is one of the most critical and complicated components of a cyclotron. The RF cavity of SC200 was designed with double cavities, second harmonic acceleration and a resonant frequency of 91.5 MHz. The Dee voltage was calculated within the range 60-120 kV at rated power of 80 kW by cold test and simulation [1, 2]. The Dee voltage of RF cavity accelerates the charged particles to achieve required energy. The peak voltage of Dee is a key parameter for RF cavity. Balanced Dee voltage is very important for effective beam centring and beam extracting [3, 4].

The peak voltage of Dee of RF cavity was calibrated by X-ray measurement using the method of bremsstrahlung. The Dee voltage was determined by the power fed to RF cavity. It is better to conduct the X-ray measurement during a low-power (~20 kW) test, rather than the rated power (about 80 kW) test. First, a thick iron yoke is assembled outside RF cavity during 80 kW operation in SC200 cyclotron. It is not easy to cross the iron yoke to make the X-ray measurement. The X-ray measurement also changes the structure of the iron yoke. Second, a superconducting coil provides ~3 T magnetic field around the RF cavity during 80 kW operation, which may affect electrical performance of X-ray detector. Taking into account these two reasons, it is convenient to make the X-ray measurement in the independent RF cavity with ~20 kW power test [5].

The design of X-ray measurement is introduced in section *Design of X-ray measurement*. According to the theory of photon transmission, a suitable shielding cover was chosen and the feasibility of the X-ray detector was verified as presented in *Theoretical verification of the design*. Finally, the needed X-ray detector was calibrated and the peak voltage of Dee was obtained at power of 10-20 kW.

DESIGN OF X-RAY MEASUREMENT

While RF cavity is in RF operation, the electrons escaping from the Dee and the liner are accelerated in the RF field, and then they emit a bremsstrahlung spectrum after hitting a metal surface [6]. The spectrum can be measured by an X-ray detector. There are several different processes that X-ray photons interact in. In the energy range of 0-200 keV, the most important processes are the photoelectric interaction. The maximum value of the spectrum energy corresponds to the peak

---

* Corresponding author; e-mail: chengen@ipp.ac.cn

250

G. Liu, *et al*.: X-Ray Calibration of Dee Voltage of Radiofrequency Cavity Based ...
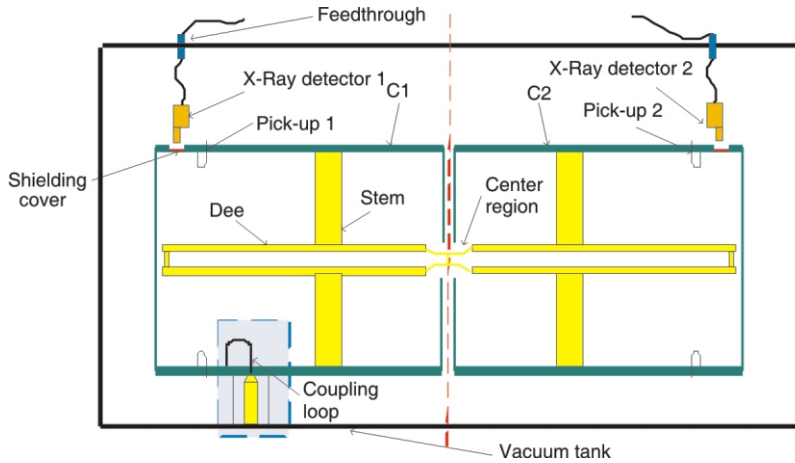Nuclear Technology & Radiation Protection: Year 2019, Vol. 34, No. 3, pp. 249-255

Figure 1. Scheamtic diagram of X-ray calibration measurement for RF cavity

voltage of Dee. Therefore, the peak voltage of Dee can be achieved by obtaining and analyzing the acquired spectrum. The schematic diagram of X-ray calibration measurement is shown in fig. 1. The C1 is the left single cavity, C2 is the other symmetrical cavity but without a coupling loop. Two pick-ups were used to collect the voltage signal in each cavity. The RF cavities and the X-ray detectors were in a vacuum tank. The X-ray detectors were fixed at the upper end of the symmetrical double cavities.

The X-ray detector was introduced straight into the outermost end of the Dee where peak voltage is reached. A 20 mm hole was made under the X-ray detector to ensure a good view of the appearance of bremsstrahlung spectrum. In order to ensure that RF cavity was closed and operational, the hole was covered by a thin shield as shown in fig. 2. Moreover, the thickness and the material of the shielding cover were chosen according to the theory of photon transmission in *Theoretical verification of the design*, which ensures the efficiency of acquiring the bremsstrahlung spectrum.

The X-ray detector is a 5 mm × 5 mm × 1 mm cadmium telluride diode detector with a ~1.5 keV FWHM at 122 keV. The feasibility of the X-ray detector is verified for this measurement in *Theoretical verification of*
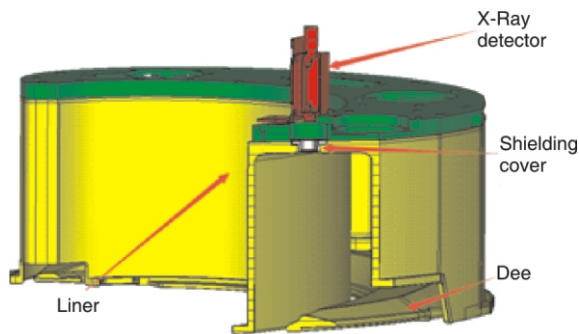
the design. A feedthrough which provided the connection of the inner and outer cables was fixed through the vacuum tank as shown in fig. 1. The X-ray detector was connected to a digital pulse processor PX5 outside the vacuum tank. The PX5 processed the signal from the X-ray detector and analyzed the channel of the spectrum. An analytical software DDPMCA provided data acquisition, display, and control of the processor PX5 [7].

THEORETICAL VERIFICATION OF THE DESIGN

In this section, the theory of photon transmission was introduced and X-ray spectrums from Dee copper with different shielding covers were compared. The optimal shielding cover was chosen according to the comparison results. The feasibility of the X-ray detector was verified.

When a beam of energetic photons (X-rays or gamma rays) passes through a material the result is a simple exponential attenuation of the primary beam. Each of the possible interaction processes can be characterized by a probability of occurrence per unit path length in the absorber. The sum of probabilities for individual processes is the total probability per unit length that the photon is removed from the beam [8]. This is termed linear attenuation coefficient, μ, and its unit is inverse length [cm^{-1}]. The number of primary photons transmitted through thickness, t, is

$$I_{tra} = I_0 e^{-\mu t} \qquad (1)$$

where I_0 is the flux of incident photons, t – the thickness of the attenuator. The number of primary photons interacting in a thickness t is obvious

$$I_{int} = I_0 (1 - e^{-\mu t}) \qquad (2)$$

Since interaction mechanisms are energy dependent, linear attenuation coefficient greatly depends on energy. Attenuation is often described by using mass attenuation coefficient μ/ρ [cm^{2}g^{-1}], where ρ is

Figure 2. Layout of X-ray calibration measurement for 1/4 cavity

G. Liu, *et al*.: X-Ray Calibration of Dee Voltage of Radiofrequency Cavity Based ...
Nuclear Technology & Radiation Protection: Year 2019, Vol. 34, No. 3, pp. 249-255

251

the density of the medium. The mass attenuation coefficient of common materials is obtained from [9].

According to the relation between power loss of RF cavity and shunt impedance

$$P \quad V^2 / 2R \qquad (3)$$

where P is the feeding power, V – the Dee voltage, R – the shunt impedance. The peak voltage of Dee changes with power, but shunt impedance is usually a constant. The shunt impedance was about 90 k obtained by simulation and cold test. The peak voltage of Dee was calculated and it amounted to about 60 kV at 20 kW. Therefore, the corresponding maximum energy of the X-ray was about 60 keV according to bremsstrahlung. Based on the calculation method of integrated over-angle X-ray spectrum as a function of photon energy [10], the X-ray spectrum from Dee copper was recalculated at maximum photon energy of 60 keV provided by MATLAB. The X-ray spectrum from Dee copper was the theoretical and original spectrum without shielding shown in fig. 3. As mentioned in *Design of X-ray measurement*, a shielding cover was used to ensure that RF cavity was closed and operational. The shielding cover could not greatly affect the original spectrum. Therefore, four different shielding covers were discussed and compared in order to choose the optimum shielding. The mass attenuation coefficient of copper and aluminum were interpolated by using the linear-logarithmic method. Taking the X-ray spectrum from Dee copper as the flux of incident photons I_0, the X-ray spectrums from Dee copper with four different shielding covers were calculated by eq. (1) as shown in fig. 3. The results indicated that the 1 mm aluminum shielding cover had minimum impact on the X-ray spectrum from Dee copper between 10 keV and 60 keV. The more X-ray photons per keV per electron, the higher detection efficiency of the X-ray measurement. The 1 mm aluminum shielding cover not only ensured that RF cavity was closed and operational, but also that it provided highest detection efficiency for X-ray measurement. It was the optimum and used in X-ray measurement.
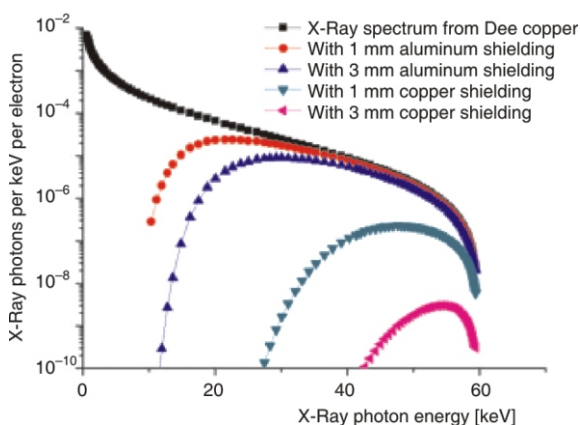

Figure 3. The effect of different shielding covers on the X-ray spectrum from Dee copper
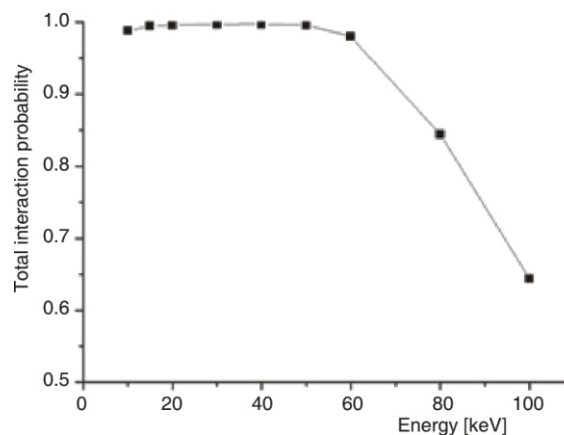

Figure 4. Total interaction probability of X-ray detector between 10 keV and 100 keV

The X-ray detector consisted of a 1 mm thick cadmium telluride positioned behind a 100 μm beryllium window. The mass attenuation coefficient of cadmium telluride and beryllium could also be obtained. According to eqs. (1) and (2), the total interaction probability (efficiency) was calculated as shown in fig. 4. The efficiency was more than 97.9 % in the energy range 0-60 keV. It indicated that this detector was suitable for ~20 kW power test.

X-RAY MEASUREMENT AND DISCUSSION

Channel calibration for the detector

As mentioned in *Design of X-ray measurement*, PX5 processed the signal from the detector and analyzed the channel of the spectrum. In order to get the
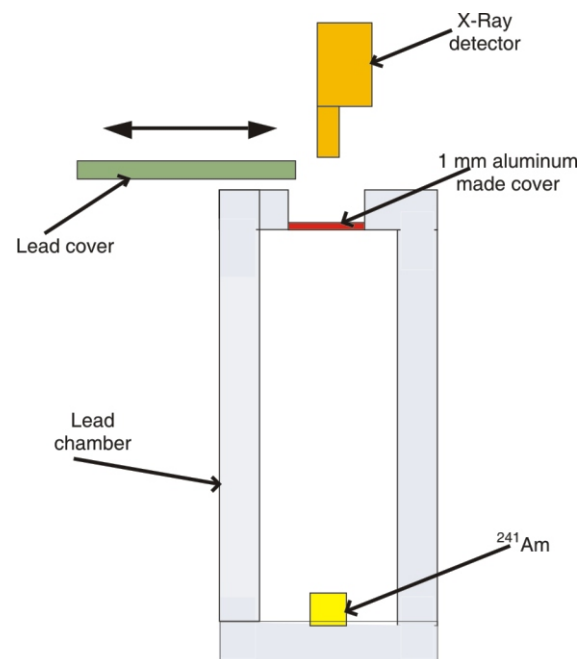

Figure 5. Schematic diagram of channel calibration for the detector

252

G. Liu, *et al*.: X-Ray Calibration of Dee Voltage of Radiofrequency Cavity Based ...
Nuclear Technology & Radiation Protection: Year 2019, Vol. 34, No. 3, pp. 249-255

relation between energy and the channel, it was necessary to calibrate the detector as shown in fig. 5. The main characteristic peak of [241]Am was 59.54 keV, which was close to the max energy (60 keV) of theoretical X-ray spectrum from Dee. The source [241]Am was used to calibrate the detector. Its volume was about 0.4 cubic centimetres and the activity was 0.1 mCi, which was suitable for the X-ray detector. A lead chamber helped obtain a collimated X-ray for the detector, and also ensured radioactive safety for humans. The height of the lead chamber was 100 mm, the thickness of the wall was 10 mm, and the internal diameter was 15 mm. The lead cover enabled the removal of the source for the fast threshold at the beginning. It was expected that the 1 mm aluminum cover which was fixed at the exit of the lead chamber would help avoid its influence on the X-ray measurement of the RF cavity.

The gain of the preamplifier in the detector was controlled by the DDPMAC. The spectrums of 241 were acquired with different gains as shown in fig. 6. In case of a certain number of channels, the smaller the gain, the larger the energy range. The gain can be chosen according to the energy range of the measured spectrum. Due to different parameters in automatic acquisition, the counts in these three pictures differ. The two peaks of americium spectrum (13.95 keV and 59.54 keV) were used to calibrate the channel of X-ray detector.

The X-ray measurement of the Dee voltage of RF cavity

A low-power (~20 kW) test was conducted for the prototype RF cavity as shown in fig. 7. The cavity was placed in a vacuum tank. The cavity could be fed ~20 kW continuous wave power without reflection after RF conditioning. The cavity was controlled to keep coupling state at 91.5 MHz by the Low Level RF (LLRF) control system [11]. The spectrums of RF cavity were recorded at power of 10-20 kW. The gain of the detector was 8.2 in order to acquire a full spectrum. The time needed to acquire the spectrum was about 180 seconds. It was necessary to wait for 10-15 minutes before increasing the power fed into the cavity and recording the spectrum. As an example, the spectrums of the two cavities at 15 kW are shown in fig. 8. The spectrum of C1 is a little harder than that of C2. The maximum value of the spectrum energy corresponded to the peak voltage of Dee according to bremsstrahlung as mentioned in *Design of X-ray measuremen*t. Peak voltages of the cavity could be obtained at different power. The corresponding shunt impedances were calculated according to eq. (3) as shown in tab. 1. However, the shunt impedance was calculated to be about 90 k through the results of simulation and cold test. The peak voltage of Dee ver-
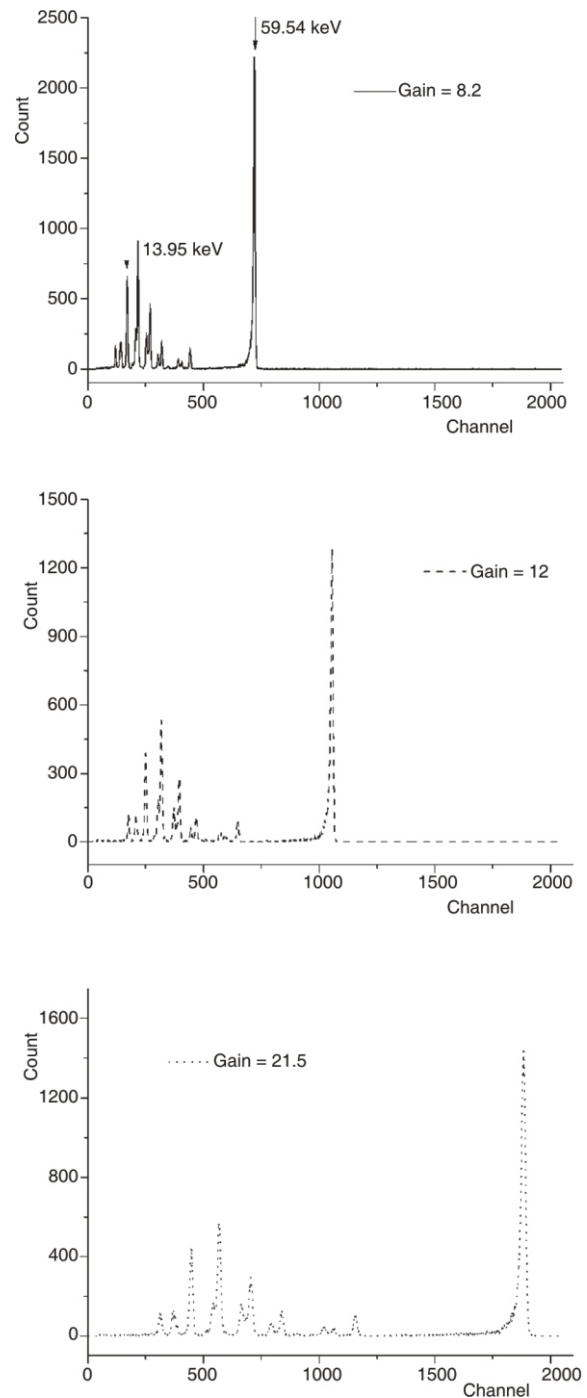

Figure 6. The acquired spectrums of [241]Am with different gains

sus power could be estimated at shunt impedance of 90 k . The comparisons of measured and calculated values of Dee peak voltage are shown in fig. 9.

The peak voltages of C1 were always a little higher than those of C2. The shunt impedance of C1 was calculated to be about 91.6-97.2 k at power of 10-20 kW and that of C2 was about 83.4-88.1 k . The shunt impedance of X-ray measurement was close to the results of simulation and cold test. The peak voltage of Dee was calibrated in this way.

Table 1. Maximum energy of the spectrum, peak voltage and shunt impedance of two cavities versus power

Power [kW]	10	12	15	17	19	20
Maximum energy of spectrum of C1 [keV]	44.21	48.33	52.41	57.17	59.43	61.50
Peak voltage of C1 [kV]	44.21	48.33	52.41	57.17	59.43	61.50
Corresponded shunt impedance of C1 [k]	97.73	97.32	91.56	96.13	92.95	94.56
Maximum energy of spectrum of C2 [keV]	41.51	45.15	50.00	54.73	57.77	59.21
Peak voltage of C2 [kV]	41.51	45.15	50.00	54.73	57.77	59.21
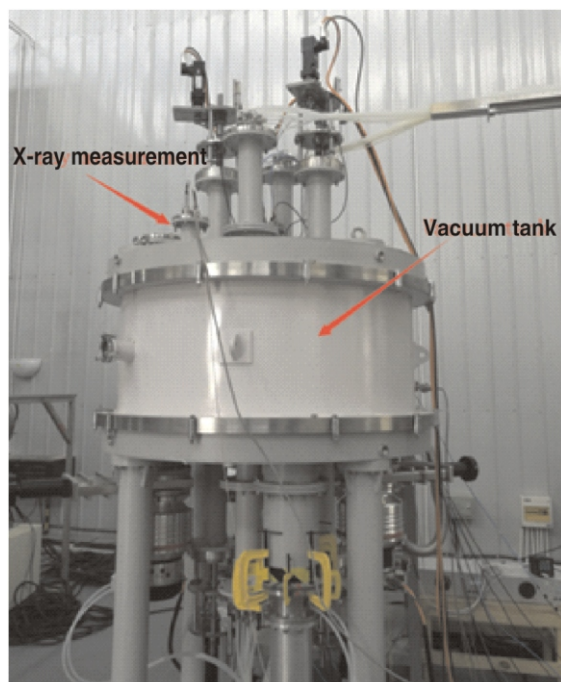
Figure 7. A low-power (~20 kW) test for RF cavity

Figure 9. The peak voltage of Dee *vs*. power

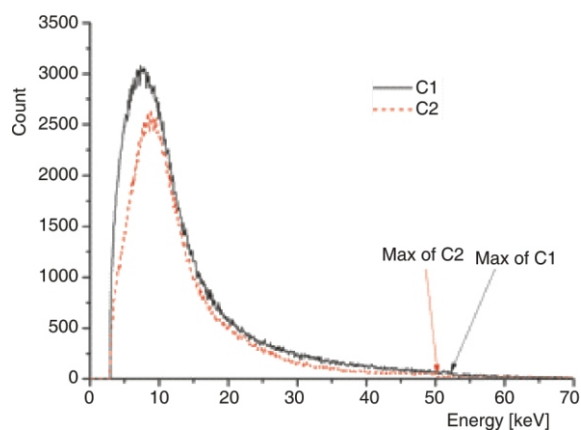**Figure 10. Amplitude of pick-up voltage *vs*. power**

Figure 8. Spectrums of the two cavities at feeding power of 15 kW; (C1 is the cavity with a coupling loop and C2 is the other one without a coupling loop as mentioned in *Design of X-ray measurement*)

Discussion of Dee voltage balance

As mentioned in *Design of X-ray measurement*, pick-ups were used to collect the voltage signal by LLRF. The amplitude of pick-up voltage signal was calculated by a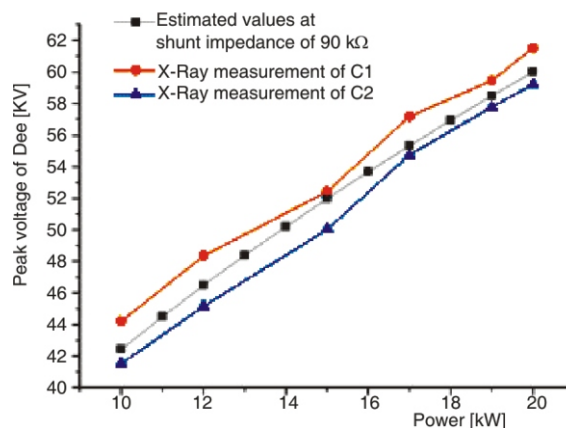 Digital *I/Q* Demodulator as 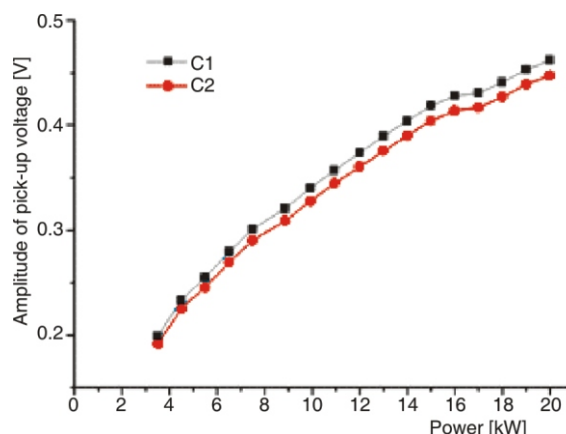shown in fig. 10 [12]. The pick-up probes of the two cavities were fixed symmetrically as shown in fig. 1. The pick-up voltages reflected the balance situation of Dee voltage of the two cavities, which was the same as the function of the peak voltage of Dee obtained by X-ray measurement. The pick-up voltage of C1 was always a little higher than that of C2. Voltage ratio of C1 to C2 *vs*. power is shown in fig. 11. The voltage ratio of C1 to C2 from pick-ups was about 1.036. The voltage ratio from X-ray measurement was about 1.029-1.070 with an average value of 1.051. The pick-up voltage ratio of C1 to C2 was quite close to that of the X-ray measurement. This X-ray measurement could be verified by the results of pick-up voltage. Because of the coupling loop, the two cavities were not strictly symmetrical in
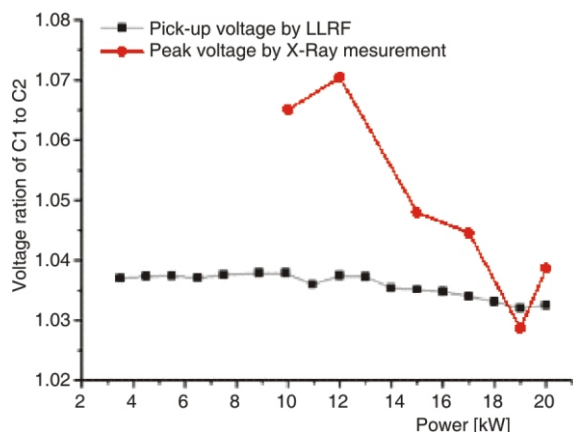
254

G. Liu, *et al.*: X-Ray Calibration of Dee Voltage of Radiofrequency Cavity Based ...
Nuclear Technology & Radiation Protection: Year 2019, Vol. 34, No. 3, pp. 249-255

Figure 11. Voltage ratio of C1 to C2 *vs*. power

fig. 1. There was a slight difference in Dee voltage between the two cavities. But the Dee voltage deviation between the two cavities was within 7 %. The Dee voltage balance of the two cavities was acceptable as obtained through X-ray measurement and the comparison of pick-up voltages.

CONCLUSION

The X-ray measurement for RF cavity was designed to calibrate the peak voltage of Dee. The measurement was demonstrated and a suitable shielding was chosen according to the theory of photon transmission. The needed X-ray detector was calibrated by using ^{241}Am. The peak voltage of Dee was obtained at power of 10-20 kW. The shunt impedance of C1 (the cavity with a coupling loop) was calculated to be about 91.6-97.2 k   and of C2 (the other cavity without a coupling loop) was about 83.4-88.1 k . The shunt impedance of X-ray measurement met the design value of 90 k . It indicated that the peak voltage of Dee was calibrated. The voltage ratio of C1to C2 obtained from pick-ups was about 1.036 and that from X-ray measurement was about 1.029-1.070 with an average value of 1.051. The results of pick-ups matched with the X-ray measurement. The Dee voltage deviation between the two cavities was within 7 %. The Dee voltage balance of the two cavities was acceptable.

ACKNOWLEDGMENT

AUTHORS' CONTRIBUTIONS

The manuscript was written by G. Liu and the figures and tables were prepared by G. Liu. The theoretical verification was carried out by Y. Song. The measurement design was conceived and prepared by G. Chen and A. Caruso. The measurement test was performed by Y. Zhao, G. Liu, and X. Zhang. L. Calabretta provided the scientific support for the measurement design.

REFERENCE

[1] Chen, G., *et al.*, Preliminary Design of RF System for SC200 Superconducting Cyclotron, *Proceedings*, Cyclotron, Zurich, Switzerland, 2016, pp. 208-211
[2] Chen, G., *et al.*, Research and Development of RF System for SC200 Cyclotron, *Proceedings*, IPAC'18, Vancouve, BC, Canada, 2018, pp. 3616-3618
[3] Timmer, J. H., Rocken, H., PA Komorowski, DEE Voltage Calibration for the ACCEL Proton Therapy Cyclotron, *Proceedings*, ICAP 2006, Chamonix, France, 2006, pp. 102-105
[4] Shengyun, Z., *et al.*, A New Method for Measuring Cyclotron RF Voltage (in Chinese), *Atomic Energy Science and Technology, 33* (1999), 3, pp. 66-69
[5] Som, S., *et al.*, Radio Frequency Cavity Analysis, Measurement, and Calibration of Absolute Dee Voltage for K-500 Superconducting Cyclotron at VECC, Kolkata., *Rev. Sci. Instrum., 84* (2013), 2, 023303
[6] Sura, J., *et al.*, X-Ray Calibration of the Superconducting Cyclotron DEE-Voltage, Report INFN-LNS, Catania, Italy, 1995
[7] ***, Products Introduction, Available on website: http://amptek.com/products/
[8] Knoll, Glenn, F., *Radiation Detection and Measurement*, John Wiley & Sons, New York, USA, 1989
[9] Hubbell, J. H., Seltzer, S. M., Tables of X-Ray Mass Attenuation Coefficients and Mass Energy-Absorption Coefficients, NISTIR 5632, Gaithersburg, Md., USA, 2004
[10] Duke, J. P., *et al.*, Measurements of RF Cavity Voltages by X-Ray Spectrum Measurements, *Proceedings*, The 10th International Linac Conference, Monterey, Cal., USA, 2000, pp. 164-165
[11] Liu, G., *et al.*, Thermal Consideration and Optimization for High-Power Operation of a Cyclotron RF Cavity, *Nuclear Inst. and Methods in Physics Research A, 908* (2018), 11, pp. 143-147
[12] Ziomek, C., Corredoura, P., Digital *I/Q* Demodulator, *Proceedings*, Particle Accelerator Conference, Stanford Linear Accelerator Center, Stanford, Cal., USA, 1995, pp. 2663-2665

G. Liu, *et al.*: X-Ray Calibration of Dee Voltage of Radiofrequency Cavity Based ...
Nuclear Technology & Radiation Protection: Year 2019, Vol. 34, No. 3, pp. 249-255

255

Гуанг ЉУ, Jуентао СУНГ, Ген ЧЕН, Jанбинг ЦАО,
Антонио КАРУЗО, Лучано КАЛАБРЕТА, Син ЦАНГ

КАЛИБРАЦИЈА НАПОНА НА ДУАНТИМА РАДИОФРЕКВЕНТНЕ ШУПЉИНЕ ПРИМЕНОМ Х-ЗРАЧЕЊА НА ОСНОВУ ТЕСТА НИСКЕ СНАГЕ

Радиофреквентна шупљина је један од најкритичнијих и најкомпликованијих компоненти циклотрона. Напон на дуантима радиофреквентне шупљине убрзава наелектрисану честицу како би постигла жељену енергију. Максимална вредност напона кључни је параметар радиофреквентне шупљине, а балансиран напон веома је битан за ефиктиван проток и екстракцију снопа. Како би се калибрисао и верификовао максимални напон на дуантима у тексту при ниској снази (20 kW) извршено је мерење применом Х-зрачења које је за радиофреквентну шупљину дизајнирано помоћу закочног зрачења. Одабран је одговарајућа заштита за радиофреквентну шупљину, а дизајн мерења Х-зрачењем је демонстриран у складу са теоријом трансмисије фотона. Коначно, максимални напон на дуантима добијен је при снази од 10-20 kW и верификован је баланс напона.

Кључне речи: циклотрон, радиофреквентна шупљина, напон на дуантима, закочно зрачење,
   тест при ниској снази