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Beam current calibration for Coulomb sum rule experiment in JLab Hall-A

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Abstract: To obtain the cross section of electron scattering on different cryogenic targets (^{2}H, ^{4}He, ^{12}C, ^{56}Fe, ^{208}Pb) for the Coulomb sum rule (CSR) measurement in JLab Hall-A, the beam current monitor (BCM) was calibrated more reliable than before at different current settings (0.2, 0.5, 1, 2, 5, 10, 20, 40, 60 μA) to determine the beam charge precisely at different kinematic settings.

Key words: Coulomb sum rule; BCM calibration; beam charge

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Hall-A 库仑求和规则实验束流刻度

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摘要:在JLab的A大厅上的库仑求和规则(CSR)实验中,为了得到CSR实验所必需的电子对不同低温靶(氢,氦,碳,铁,铅)的散射截面,对束流监测器在不同的电流值(0.2,0.5,1,2,5,10,20,40,60 μA)进行了更好地刻度,以得到不同运动学参量下更精确的束流电荷.

关键词:库仑求和规则;束流电流监测器刻度;束流电荷

0 Introduction

Studying the properties of nucleons in a nuclear medium is an essential objective in nuclear physics. It might make a connection between the low energy theories and the high energy theory of quantum chromo dynamics (QCD). The charge response of nucleus is one of the effects of nuclear medium which could be studied by the Coulomb sum rule (CSR)[1-5]. This sum rule states that when integrating the longitudinal response function R_L of quasi-elastic electron scattering of nuclei over the full range of energy loss ω at a large enough three-momentum transfer $|\mathbf{q}| = q$ (greater than twice the Fermi momentum, $q \geqslant 500$ MeV/c), one should count the number Z of protons in a nucleus.

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More explicitly the quantity $S_L(q)$ defined by

$$S_L(q) = \frac{1}{Z}\int_{0^+}^{\infty} \frac{R_L(q,\omega)}{G'^2_E} d\omega \quad (1)$$

was predicted to be unity in the limit of large q. Here $G'_E = (G^p_E + N/ZG^n_E)\zeta$ takes into account the nucleon charge form factor inside the nucleus (which was usually taken to be equal to that of a free nucleon), ζ is a relativistic correction[6]. The lower limit of integration 0^+ excludes the elastic peak and the excited states of the nucleus. To obtain the longitudinal response function R_L, the measurement of cross section of electron scattering off targets should be done. The CSR experiment will measure the cross section of quasi-elastic electron scattering on five different targets (H, He, C, Fe, Pb) at four different scattering angles (15°, 60°, 90°, 120°) with different beam energies from 0.4 GeV to 4.0 GeV. The cross section expression is as follows:

$$\frac{d^2\sigma}{d\Omega d\omega} = \frac{N_{detected}(1.0+\varepsilon_i)(1.0+DT)}{\left(\iint \frac{\rho N_A}{A} dx\right)\left(\iint \frac{I}{e} dt\right)\left(\int d\Omega d\omega\right)}, \quad (2)$$

Where $N_{detected}$ is the number of events detected, ε_i is inefficiency of the detector system, DT is dead time, ρ is density of the target, N_A is avogadro number (6.022×10^{23}), A is atomic number of the target, I is beam current, e is charge of the electron (1.6×10^{-19} C).

It is important to measure the beam charge precisely for extracting the cross section. So reliable calibration of beam current monitor (BCM) system is important for obtaining the precise beam charge for different kinematic settings.

1 BCM system in Hall A

In the accelerator injector section, the 0L02 (current monitor) and Faraday cup[7] were used to provide an absolute current reference during the calibration procedure. Since the beam supplied for three different halls (A, B, C) which could request the different beam currents for the experiment, respectively, the precise measurement of beam current in the individual hall would be needed. As for Hall A, there is a BCM system (Fig. 1) located 25 m upstream the target to measure beam current. This measurement was stable, with low noise and non-interception. The BCM consisted of a parametric current transformer (Unser)[8] and two resonant cavities upstream and downstream①. The Unser monitor mentioned above provided an absolute current reference for the beam current but it was unstable. So continuous monitoring of the current was accomplished by the two resonant cavities. The output voltages of the two cavities were proportional to the beam intensity. An absolute beam charge measurement was obtained by calibrating the resonant cavities output. The frequency of output signals of resonant cavities decreased from 1 497 MHz to 10 kHz by down converters for transmission to the electronics.

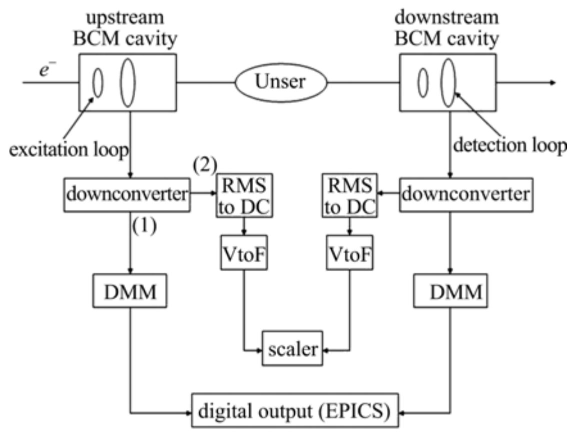

Fig. 1 The beam current monitoring system

Then, they were split into two output channels: ① the sampled data, and ② the integrated data recorded in the data stream.

The sampled data, EPICS (experimental physics and industrial control system), were processed by the high-precision digital AC voltmeter, DMM (digital multi-meter). This device provided a digital output per second which represents the root mean square (RMS) value of

① Hall A Jefferson Lab. Basic instrumentation for Hall A at Jefferson Lab, 2004.

the input signal during that second. The resulting number, $V^{(u,d)}$, was proportional to the average beam current for that second. The integrated data sent to an RMS-to-DC converter which produced an analog DC voltage level. This voltage level drove a voltage-to-frequency converter (VtoF) whose output frequency was proportional to the input DC voltage level. These signals were then fed to the Fastbus scalers and finally injected into the data stream along with the other scaler information. These scalers were simply accumulated during the run, resulting in a number which was proportional to the integrated voltage level and therefore more accurately represented the true integral of the current and hence the total beam charge. The regular RMS to DC output was linear for the currents from about 5 to 200 μA. Since it was non-linear at the low currents, the amplifiers with different gains (×3, ×10) allowed the non-linear region to be extended to lower currents and saturated at the very high currents. Hence there were 3 signals coming from each BCM cavity (U1, U3, U10, D1, D3, D10). All 6 signals were fed to the scaler readout of each spectrometer (the left and right spectrometer). Hence we had 6 scaler outputs for determining the charge during a run. Each of these scaler outputs were calibrated during the calibration runs. The following would do BCM calibration for the right spectrometer and it was a similar procedure for the left spectrometer.

2 BCM calibration

2.1 EPICS calibration

The 0L02 current monitor and Faraday cup at the accelerator injector section were used to provide an absolute current reference. During the BCM calibration run, the different current settings (0.2, 0.5, 1, 2, 5, 10, 20, 40, 60 μA) were measured. The EPICS data written to the bcmlog_131(132) file. The current for Faraday cup, 0L02 ($I_{Faraday}$, I_{0L02}) and the average voltage level of BCM cavities (V^u, V^d) were measured at the same time during the BCM calibration run when the beam only went to Hall A. The online "e05110_20595.dat.0" was the scaler data file for the right spectrometer. The EPICS calibration procedure was as follows. I_{0L02} and $I_{Faraday}$ were compared first to make sure that the absolute beam current values were reliable, Hall A "bcmlog131" file was used to calculate the results as shown in Tab. 1.

Tab. 1 Comparison between I_{0L02} and $I_{Faraday}$

I_{0L02}/μA	$I_{Faraday}$/μA	$\left(\frac{I_{0L02}}{I_{Faraday}}-1\right)$/%
59.491±0.245	59.318±0.177	0.29
39.160±0.049	39.048±0.068	0.29
19.594±0.033	19.472±0.012	0.62
10.810±0.039	10.723±0.051	0.81
5.038±0.007	5.034±0.01	0.06
2.171±0.008	2.164±0.005	0.33
1.017±0.002	1.019±0.017	0.27
0.542±0.002	0.549±6E−4	1.20
0.259±4E−4	0.263±5E−5	1.50

Clearly, Tab. 1 shows that the egality was checked at <1% level above 1 μA. And Fig. 2 shows that the ratio of 0L02 current to Faraday cup was around 1. It means that 0L02 monitor was precise enough to be used for calibration.

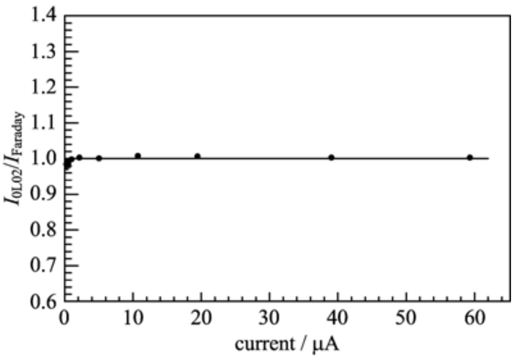

Fig. 2 The ratio of Faraday cup to 0L02 current was around 1

Then the EPICS calibration constants are as follows

$$\text{Constant}_{\text{EPICS}} = \frac{I_{0L02}}{V^{u,d} - \text{offset}} \tag{3}$$

where the offset of BCM cavities was determined from the beam off period for Hall A when the Faraday cup was inserted. The EPICS calibration constants, which were the ratio of the 0L02 current to output voltage of the cavity, were extracted from Eq. (2) with "bcmlog_132" data file.

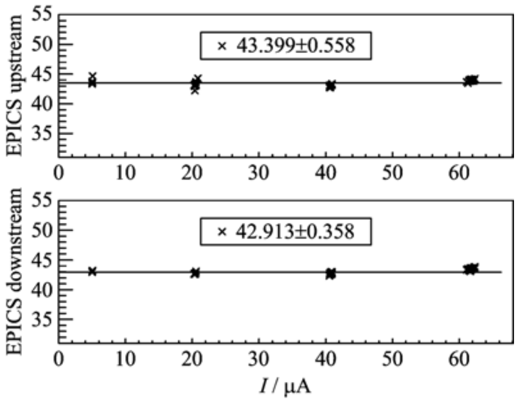

Fig. 3　The EPICS calibration constants

In Fig. 3, the X axis represents the current measured by 0L02 monitor and the Y axis represents the constants for the EPICS upstream and downstream, respectively. Fig. 3 shows that the EPICS has a good linear relation with the different current settings. The average constants for EPICS upstream and downstream were determined as 43.399±0.558 and 42.913±0.358, respectively. After getting the EPICS calibration constants, the average of beam current could be calculated by Eq. (3) for reference during the data taking period.

$$I_{av} = \text{Constant}_{EPICS} \cdot (V^{u,d} - \text{offset}). \qquad (4)$$

2.2　Scalers calibration

In order to determine the total beam charge at different kinematic settings, the constants of scalers proportional to the beam current were determined as follows:

$$\text{Constant}_{bcm\times n} = \frac{\frac{\text{Scaler}_{bcm\times n}}{\text{time}} - \text{offset}_{bcm\times n}}{I_{0L02}}, \qquad (5)$$

Where $n = 1, 3, 10$ is the gain factor of the amplifiers, time is the clock time for each kinematic setting (in seconds), and $\text{Scaler}_{bcm\times n}$ is the BCM scaler reading for each gain factor. The $\text{offset}_{bcm\times n}$ was usually obtained from calibration runs. The calibration constants for converting the scaler to charge were extracted from the data file mentioned above using Hall A ANALYZER tool, a physics analysis software in C++ using an object-oriented approach. The zero offsets for scaler rate are 362.5, 350.2, 442.6, 160.1, 126.7, 321.1 Hz for the U1, U3, U10 and D1, D3, D10, respectively. The calibration constants of the scalers shown in Fig. 4 were extracted from Eq. (4) for the different current settings: 0.2, 0.5, 1, 2, 5, 10, 20, 40, 60 μA, respectively.

In Fig. 4, the X axis represents the current measured by 0L02 monitor and the Y axis represents the calibration constants for the BCM scalers upstream (left) and downstream (right), respectively. It is shown that the BCM scaler U1(3), D1(3) is of good linearity for the current range from 5 to 60 μA and gets worse when the current is lower than 5 μA. The BCM U10 and D10 work well around 30 μA and get saturated when the current is higher.

After obtaining these calibration constants, the beam charge for corresponding kinematic setting could be determined. The beam charge would be derived from the BCM scalers as follows:

$$Q_{bcm\times n} = \frac{\frac{\text{Scaler}_{bcm\times n}}{\text{time}} - \text{offset}_{bcm\times n}}{\text{Constant}_{bcm\times n}}\text{time}, \qquad (6)$$

where $Q_{bcm\times n}/\mu$ C is the beam charge calculated for the corresponding gain factor at a kinematic setting. The other variables have been mentioned above. Tab. 2 is the total beam charge extracted from the EPICS and BCM U3, D3 scaler, respectively.

Tab. 2　Beam charge calculation for different targets at electron scattering angle 15°

E/GeV	p_0/GeV	target	Q_E/C	Q_S/C	δQ/%
3.249	2.724	^{2}H	0.003 01	0.003 05	1.3
2.445	1.914	^{4}He	0.004 94	0.005 04	2.0
2.445	2.360	^{12}C	0.006 96	0.006 94	0.29
4.045	3.396	^{56}Fe	0.004 87	0.004 73	2.9
3.249	2.540	^{208}Pb	0.003 02	0.002 99	1.0

E, p_0 are the beam energy and central scattering momentum in GeV. Q_E/C and Q_S/C are the average beam charge calculated from EPICS

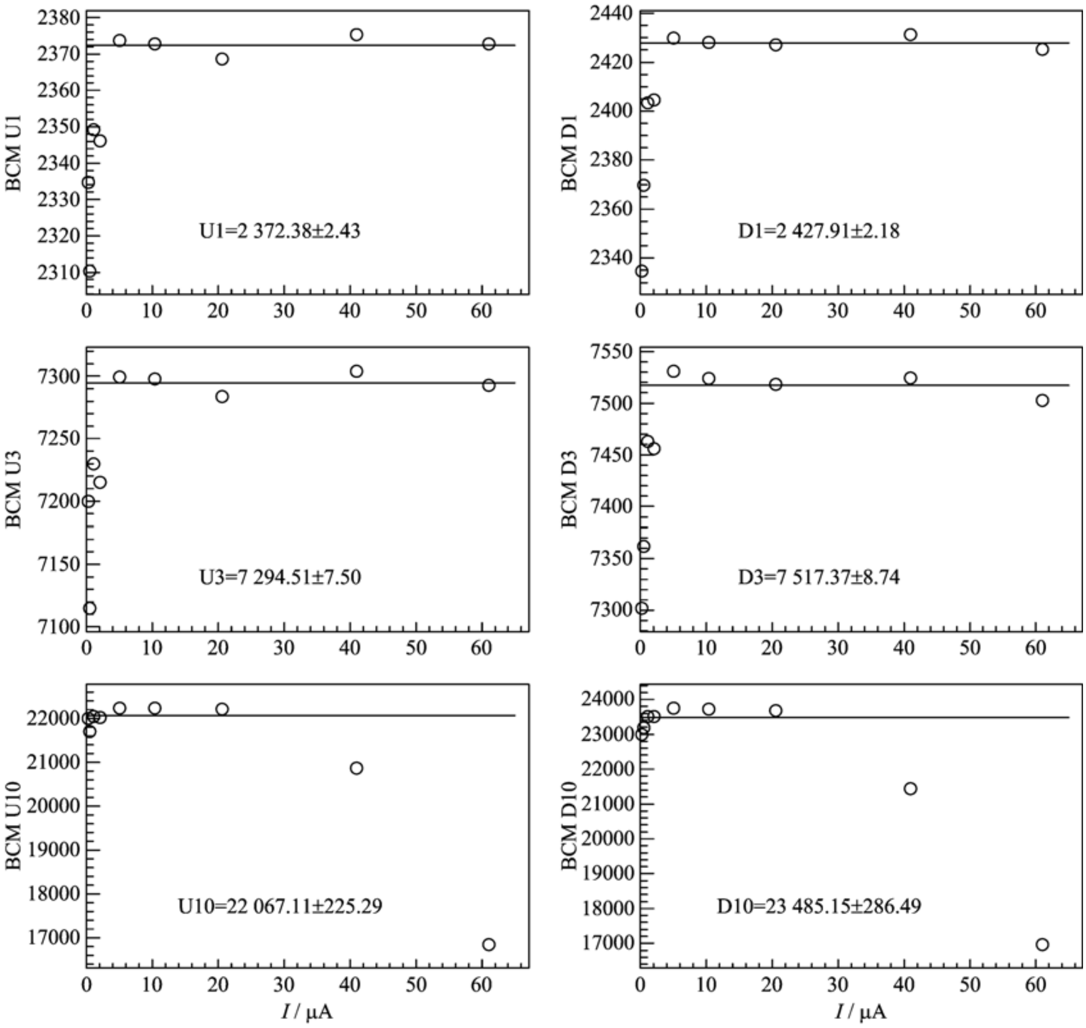

Fig. 4 The BCM upstream and downstream cavity data in the left and right plot, respectively

and the total beam charge obtained from the BCM scalers, respectively. δQ is the difference between Q_E and Q_S, and it shows that the maximum and minimum deviations are 2.9% and 0.29%, respectively.

3 Conclusion

The Coulomb sum rule experiment sets beam currents from 5 to 60 μA due to the BCM calibration result. As the Unser monitor was unstable, the 0L02 monitor was used for BCM calibration. Using this calibration constants of scalers, the total beam charge for the different kinematic settings is extracted. It shows that the result of BCM calibration is more reliable, and the BCM scaler calibration constants can be used to calculate the beam charge more precisely to analyze the cross sections for different targets.

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