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High Accuracy Field Integral Measurement for CEBAF Beam Energy Determination

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Abstract - **The determination of the beam energy in the experimental hall A of CEBAF accelerator (now TJNAF) is done through a very accurate measurement of the field integral of a reference dipole, electrically connected in series with the bending magnets transporting the beam from the accelerator to the experimental area.**

A new method is used to determine the field integral; this method will be described, as well as the calibrations done in the laboratory. Finally, the goal to reach an accuracy of a few 10^{-5} on the field integral has been reached, as it will be suggested by comparing the results of the beam energy determination obtained on the accelerator with this method to results obtained by other independant methods.

I. INTRODUCTION

The scientific program in the Hall-A of CEBAF focuses on the precise measurement of nucleons and light nuclei properties by electron scattering. This program requires an accurate determination of all the parameters describing the kinematics of the reaction, like the angle and momentum of the scattered electron, as well as the incident beam direction and energy.

Based on a physics case, the specification for the beam energy knowledge in absolute was set to $\Delta E/E = 10^{-4}$ in the range 0.5 to 6 GeV. This goal is by one order of magnitude more demanding than what the accelerator has been able to provide so far ; the point is that an accurate energy determination is much more difficult to obtain on beam extracted from linacs like CEBAF than on circular accelerators like LEP, where the resonant beam depolarization technics can be implemented.

After an extensive investigation of the possible methods, two projects were selected for CEBAF : the 'e, p' measurement, based on angle measurements in a two-bodies kinematics [1] , and the 'ARC' project, based on the use of a section of the beam transport line as a magnetic spectrometer [2]. This paper reports on the part of the ARC project devoted to the field integral measurement.

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II. THE ARC MEASUREMENT

A. General principle

This method takes profit of an existing 40 m long bending section of the beam line (the 'arc'), located between the accelerator and the Hall-A end station. The arc is made of 8 dipole magnets and 9 quadrupole magnets, resulting in an achromatic beam deflection of 34.3° (nominal angle).

This arc can also operate in a fully dispersive mode by turning off the quadrupoles. In this mode, the energy E, the field integral of the 8 dipoles along the path of the beam $\int B*dz$ and the net bend angle through the arc θ are related by :

$$E= c *(\int B*dz)/ \theta \qquad (1)$$

where c = 0.299792 GeV* radian/T m is the speed of light in convenient unit.

Due to the specific design of the arc dipoles (uniform field within parallel faces), small changes in the beam input parameters will not affect the field integral in the case of dispersive mode. So the field integral is a well defined quantity and the ARC method consists in two simultaneous measurements, performed during dispersive mode operation : the field integral, based on a reference magnet, and the actual beam bend, based on a set of wire scanners. The beam energy is then given by (1).

Practically, no field measurement set up could be implemented on the arc dipoles as their gap is fully occupied by the vacuum pipe of the beam. So, a 9[th] dipole, identical to the 8 arc dipoles, called the reference dipole, was installed in a specific building, out of the beam line ; it is powered in series with the arc magnets and equipped with a device measuring its field integral within a few 10^{-5} accuracy . As each of the arc dipole has been previously calibrated relatively to the reference dipole, this relative calibration, done once for ever, and the absolute reference magnet measurement, done at each energy change, provide the required arc field integral.

B. Field integral measuring device

The field integral measuring device uses an original technique, which has already been described [2,3]. It makes use of the well known 'translating coil' technique, where the flux changes through a small coil are recorded while the coil travels inside the gap along the beam path ; but here, we make use of a special arrangment of two coils accurately spaced at a distance about the magnetic length of the reference magnet, and connected in series. This design results in a 'zero-measurement' giving an unprecedented accuracy in terms of field integral measurement. Assuming that the first coil final position is close to the second coil initial position, that the field is zero at the first coil initial position and at the second coil final position, and that both measuring coils have the same area, one can show that :

$$\int_A^B dx \int_{t(A)}^{t(x)} V(t')\ dt' = -\left(\int_A^{B+L} Bdz - B_0 * L\right) * S \qquad (2)$$

where
. A and B are the departure and arrival points of the first moving coil ;
. A + L = B and B + L the corresponding points of the second moving coil ;
. V is the output voltage of the two coils in series ;
. B_0 is the central field at point B ;
. L is the distance between the axis of the two coils ;
. S is the average magnetic area of the two coils.

Equation (2) shows that the double integral measurement consists of the difference between the true and assumed field integrals ; it is small compared to the field integral itself. Therefore, as far as B_0 and L are known with high accuracy, a given relative uncertainity in the measurement itself (left hand side of (2)) will result in a much smaller relative uncertainity in the determination of $\int B*dz$.

In this measuring method, there are only two parameters to be measured with an accuracy of about 10^{-5} :
. the distance L between the mechanical axis of the two coils ;
. the central field B_0 for each measurement.

By comparing the data recorded during forward and backward pass, one can correct the measurement from the offset of the voltmeter due to the drift and, at first order, from the difference between the area of the two coils.

III. THE EXPERIMENTAL APPARATUS

As most of the experimental apparatus has been described in [3], we will only evoke here a brief description.

A. *The search coils*

To avoid second order effects and to provide a consistency check in the comparison between forward and backward data, the two coils must be identical in terms of magnetic area within a relative accuracy of a few 10^{-5}. Moreover, these coils must have an area large enough to get a significant output voltage.

Each search coil consists of two elementary parts connected in series :
. the main coil, which has an area of about 1 m^2 ;
. the compensation coil, which is wound in such a way that one can ajust carefully its number of turns. A single turn has an area of about 10^{-5} m^2. So, it is possible in principle to balance the search coils area with a relative accuracy of 10^{-5}.

Several sets of search coils where calibrated and then balanced using a rotating device inserted in a homogeneous dipolar field and connected to a lock-in amplifier. By carefully adjusting the number of turns of the compensation coil, it was possible to minimize the residual area between two coils to less than $\pm$ 1.5 10^{-5} m^2.

A special attention was given to the measurement of the distance L between the mechanical axis of the search coils after mounting. This was done on a tridimensional control apparatus, calibrated with a 3000.006 mm long invar standard. The effect of the temperature on this distance was also measured between 21 and 35 °C. A fit of these measurements gives the distance L versus the temperature T of the supporting structure :

$$L = (3039.635 \pm 0.020)\ [\ 1 + C_T\,(T - 21)] \qquad (3)$$

with L in mm, T in °C and with :

$$C_T = (16.5 \pm 1.0) \quad 10^{-6}\,(\,°C)^{-1} \qquad (4)$$

The distance L must be corrected at each end of the distance between the mechanical coil axis and their magnetic center. For this, the same setup as for the coil area adjustment was used, but inside a quadrupolar field. Typical off-centerings of 10 µm were measured with an accuracy of 2 µm.

B. *The NMR probes*

A set of four NMR probes (Metrolab, Switzerland) was used to measure the central field in the whole range of the energy beam, from 0.043 to 1.06 T (the energy/field ratio is 12.03 Gev/T), with an accuracy of 2 ppm.

C. *The mechanical parts*

The mechanical parts of the system consist mainly of :
. the reference dipole support ;
. the 6 m long measuring system support : its main actuator is a motor-driven screw which enables to move the measuring system on a distance of about 3 m in 5 sec ;
. the moving measuring system, consisting of a 3 m long composite board on which the four NMR probes and the two search coils are mounted ;
. a 3 m long linear encoder to measure the coil position with an accurancy of about 100 µm and a resolution of 2.5 µm ;

. two µ-metal magnetic shields installed at both extremities of the measuring coil journey ; a zero field is effectively needed at position A and B + L in eq. (2), as previously mentioned.

The installation at Saclay is shown on Fig. 1.

D. The hardware and software

The integral measurement sequence is fully automatic. It consists of the following phases :
. linear encoder initialization ;
. measure of the central field by NMR ;
. forward pass flux integration ;
. backward pass flux integration ;
. check of the central field by NMR.

In addition to these measurements, 4 probe temperatures and the current in the dipole are recorded at the beginning and at the end of the sequence.

The block diagram of the hardware is shown on Fig. 2.

Displacements, specified for each measurement types, are performed by a brushless motor. This motor is controlled by a double servo loop (position and velocity) to get very accurate positioning. Feedback informations come from the incremental linear encoder and a synchro resolver. The loops are managed by an high accuracy digital P.I.D. controller (PMAC from Delta Tau, USA).

Analog voltages induced in the search coils are integrated with a precision digital integrator (PDI 5035 from Metrolab, Switzerland).

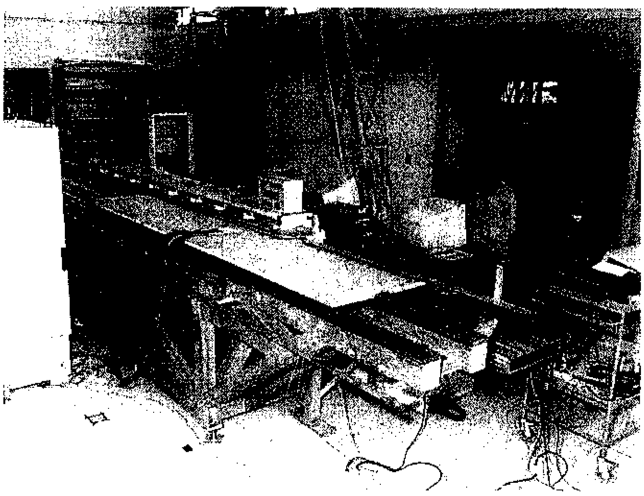

Fig.1. The integral measurement setup

A VME bus allows information exchanges between the CPU and the main boards. The CPU is also linked via the Ethernet network to Unix work stations installed in the control room.

The control system is based on the EPICS software [4]. Several displays are used to control the setup. The data from EPICS are processed off-line on an Unix station to perform the integrations and the corrections resulting in the field integral.

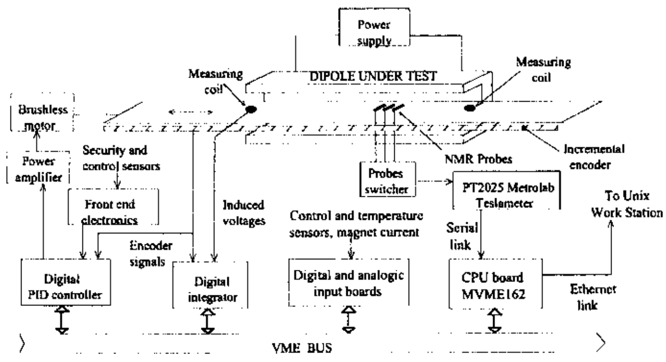

Fig. 2. Block diagram of the electronics

IV. EXPERIMENTAL RESULTS

The final aimed accuracy requires several controls and calibrations of all individual components. Besides the measurements already described in chapter II concerning the search coil and their position on the board, two more field measurements must be done before getting the final results :
. the reference dipole field mapping to correct straight field integrals for getting curvilinear field integrals ;
. the calibration of each arc dipole relatively to the reference dipole.

A. Reference dipole field mapping

In formula (1), the field integral to be taken into account is the one along the real trajectory of the beam, i.e. it is a curvilinear one ; the experimental apparatus we use can only give straight integrals. Mapping of the reference dipole on various lines parallel to the magnet axis enables to calculate the correction factor between straight (I_S) and curvilinear (I_C) integrals. This correction factor

$$C_c = (I_c - I_s) / I_s \quad (5)$$

was found to be + 1.61 10^{-4} for a current of 90 A and + 1.32 10^{-4} for a current of 300 A (iron saturation effect).

B. Calibration of the arc dipoles

Each of the arc dipoles was calibrated relatively to the reference dipole. The magnets were dismounted from the beam line and calibrated using the 'streched wire' technics on the 'dipole stand' of Jefferson Lab [5]. This device, initially designed for the acceptance tests of CEBAF dipoles, was upgraded for the arc project to a 10^{-4} absolute accuracy level and to a 10^{-5} reproducibility level.

Basically, the 'dipole stand' measures the difference ($I_i - I_9$) between the i [th] arc dipole and the 9 [th] dipole integrals. So, at a given excitation current, we use the formula :

$$I_{arc} = 8 * I_9 + \Delta I \qquad (6)$$

where :

- I_{arc} is the field integral of the whole arc ;
- I_9 is the field integral of the 9[th] magnet as measured by the integral setup ;
- $\Delta I = \Sigma (I_i - I_9)$ for i = 1, 8 is the sum of the 8 'dipole stand' measurements, for the same excitation current.

Figure 3 gives ΔI versus current for a set of currents along an excitation loop. The ΔI needed in (6) is interpolated from this curve. For example, at 150 A (3.57 GeV), one has $I_{arc} \cong$ 7128 T mm and $\Delta I \cong 9$ T mm is a 1.3 10^{-3} relative correction.

C. Final measurements

A complete calculation taking into account all the cause of errors showed that, in the energy determination, most of the error comes from the final relative error on the field integral. The relative value of the error on the energy was estimated to 1.2 10^{-4} at 0.5 GeV and 6.8 10^{-5} at 4 GeV.

Table I summarizes the beam energies measured by ARC and 'e, p' for different beam tunings.

Tab I Beam energy measurement results

Date	ARC (MeV)	e, p (MeV)
Oct 24, 98	3385 ± 0.6	3384 ± 1
Nov 6, 98	4236.2 ± 0.8	4240 ± 3
Apr 23, 99	3355.2 ± 0.7	3354.4 ± 0.7
May 29, 99	3355.1 ± 0.7	3355. 0 ± 0.7

The accuracy quoted by ARC is 2 10^{-4}, due to instabilities of the beam position recorded by the scanners (angle measurement). A fast feedback system will stabilize the beam in a near future. Concerning the 'e, p' measurement, the accuracy is governed by a systematical error of 0.7 MeV plus a statistical error depending on the measurement time. Within these errors, both methods are in good agreement.

V. CONCLUSIONS

The goal to reach an absolute accuracy better than 10^{-4} on the field integral measurement of a reference dipole has been achieved as it is suggested by comparing the energies measured for the same beam by different methods.

This could be possible using a set of translating coils in a 'zero-measurement' method with very accurate calibration of the search coils and careful corrections of the raw results.

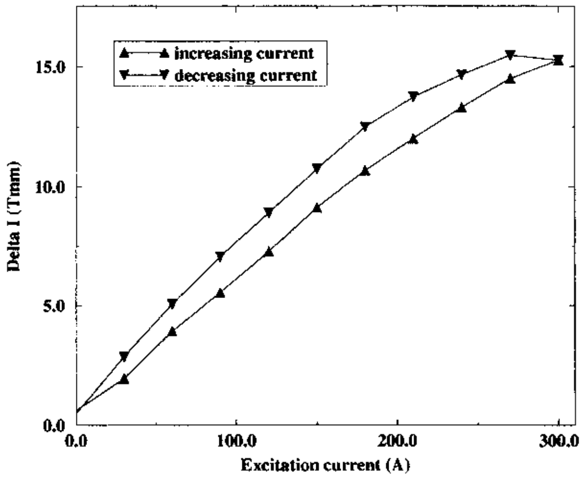

Fig. 3. ΔI integral field correction

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