

Beam Energy Measurement Using the Hall C Beam Line

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Abstract

We propose to use the curved transport line into Hall C to measure the beam energy. With only dipoles powered, this transport arc has a dispersion of 12 cm/%. We propose to insert pairs of wire scanners at the entrance and exit of the arc to measure beam position and direction. These measurements, together with a calibrated dipole field, obtain an absolute beam energy measurement with $\sim 10^{-3}$ accuracy, according to error analyses. In operational mode, arc quads and sextupoles are powered to obtain a second order achromat with a dispersion of 2.1 cm/% at the arc center. A wire scanner at the arc center then obtains a relative energy measurement of $\sim 10^{-4}$ accuracy.

I. INTRODUCTION

The Hall C beam line is sketched in Figure 1. The arc section of this beam line consists of 8 dipoles, 12 quads, 8 sextupoles, and 8 beam correctors (4 vertical and 4 horizontal). These dipoles bend the beam by a total of 34.3° , and the full 41.6 m long arc transport is designed to form a second-order achromat. We now describe the beam energy measurement method which uses that arc as proposed in refs. [1], [2], and [3]. For the absolute energy measurement only the dipoles are switched on (quads, sextupoles and correctors are off). The current in the calibrated bending magnets, which are serially connected, is varied to set the beam position to be along the center of the dipoles. The position and direction of the beam entering the arc section are measured by a pair of high resolution harps (wire scanners). The position and direction of the beam at the exit of the arc are determined by another pair of calibrated harps. From the initial position and direction measurements, the final position measurement, and the calibrated dipole field, the beam momentum can be determined. Thus the method requires accurate position measurements at the harps and an accurate determination of

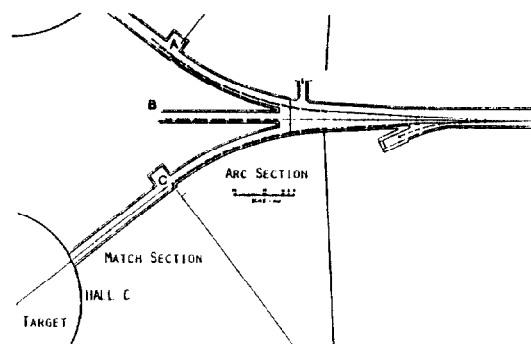


Figure 1: Hall C beam transport line.

the magnetic field integral $\int B dl$ as a function of the current I in the arc dipoles. Accurate position measurements depend on the alignment accuracy, which can be reduced to errors on the order of $100 \mu m$. Accurate field determination will require a new calibrating set of careful absolute field measurements on two (or a few) reference dipoles. In the following sections we will discuss the error analyses of these measurements. After setting an absolute energy scale with the dipoles, the quadrupoles and sextupoles are then energized to the values required for achromatic transport, and the correctors will be used to center the beam. The magnets are then fixed in strengths. Variations in beam energy can then be measured as variations in beam position at the midpoint, which has a dispersion of 2.1 cm/%. Thus, in this mode, measurable position shifts of $100 \mu m$ corresponding to relative energy shifts of 0.5×10^{-4} . As this relative measurement is not dependent on calibration errors, relative energy measurements will be substantially more accurate than the absolute determination.

II. OPERATIONAL PRINCIPLES AND OPTICAL CHARACTERISTICS OF THE ARC SPECTROMETER

An initial beam position and direction Δx and $\Delta x'$ are measured by the initial pair of harps with respect to their surveyed centerlines. The arc magnetic field is calibrated to bend a beam of a central energy P_0 the reference angle of 34.3° from harp center to harp center. The beam position

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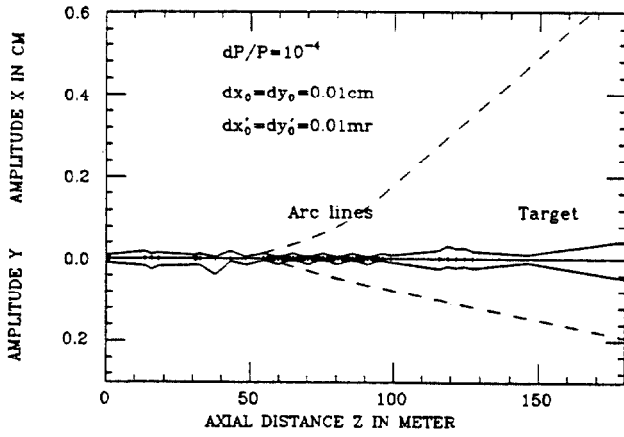


Figure 2: Beam envelope along Hall C beam line

Table 1: The major first order matrix elements of an N -dipole systems

N	ϕ ($^\circ$)	Size (cm)	R_{11}	R_{12}	$D = R_{16}$ (m)
1	4.2875	0.022	0.9064	2.0234	-0.1422
2	8.5750	0.033	1.1015	3.0322	-0.6734
3	12.863	0.045	1.2965	4.0410	-1.5938
4	17.150	0.060	1.4916	5.0498	-2.9032
5	21.438	0.078	1.6866	6.0586	-4.6017
6	25.725	0.099	1.8817	7.0675	-6.6894
7	30.013	0.124	2.0767	8.0763	-9.1608
8	34.300	0.152	2.2718	9.0851	-12.032

X_{final} at the final harp then obtains a measured energy offset of:

$$\Delta P = \frac{P_0}{\eta} (X_{final} - \Delta x - \Delta x' L) \quad (1)$$

where L is the arc length (41.6 m) and η is the dispersion at the exit of the arc (-12.03 m). The errors in the various measured quantities, calibrations, and surveying will determine the actual energy measurement error; these error sources are discussed in the next section. In normal (achromatic) operation the beam remains tightly confined. The design beam envelope along the Hall C beam line is shown in Figure 2. The initial conditions are beam widths of $\delta x = \delta y = 0.01$ cm, $\delta x' = \delta y' = 0.01$ mrad. The solid line describes the beam envelope sizes in the normal transport conditions. In absolute energy measurement mode, the arc quads are off. The beam therefore is enlarged through the arc, as shown in the dashed lines in Figure 2, in which all downstream quads are also switched off. Table 1 shows beam transport elements through the 8-dipole arc. Note that the dispersion D increases as N^2 , where N is the dipole location number. Maximum dispersive effect is therefore found by using the entire arc.

III. ERROR ANALYSIS

The proposed measurement method is planned to obtain absolute energy measurements at the $\delta E/E \approx 10^{-3}$ level. Analyses to support an estimate of errors at this level are required. An initial error analysis was obtained by [3] and the same methods were also used to study variations and changes in the proposed energy measurement configuration. In this section we describe the error analysis methods, including estimates of the expected error sources, and report results of the analyses. The various error sources and their estimated contributions include:

A. Initial harp location and direction

Surveying errors at each location should be on the order of 100 μ m. However, with an entrance harps separation of 1m, this implies an initial direction error of 100 μ rad. This 100 μ rad error translates into a 0.5 cm position change at the end of the arc, where the dispersion is about 12 m. Thus this error alone would give $\delta p/p = 0.4 \times 10^{-3}$; it is the largest estimated source in the error analysis [3]. Subsequent to that study, it was decided to increase the initial harp separation to 2.5 m. That reduces the initial direction error to 40 μ rad and the subsequent contribution to $\delta p/p$ is 2×10^{-4} .

B. Final harp location

In the error analysis, it was assumed that a random 20 μ rad missteering occurs every 10.4 m (an assumed intermediate monument location), and this accumulates to obtain a dislocation at the end of the 41.6 m arc. This corresponds to a mislocation of 200 μ m at every arc cell. It somewhat overshoots the estimate of an rms total error of 200 μ m displacement at the end of the arc, after smoothing. The total effect on the beam is an rms error of $\delta p/p = 0.05 \times 10^{-4}$.

C. Location, orientation errors, and variations in dipole integrated fields

Placement errors are assumed to be on the level of 1 mm; they have little effect. A 1 mrad roll error is also included; it changes vertical positions but does not greatly change horizontal (energy measurement plane) locations. A random dipole-to-dipole bend variation of 2.5×10^{-4} rms was also assumed. This adds a rms energy error of slightly more than 10^{-4} .

D. Quad and steering magnet effects

In the absolute energy measurement mode, the quads and steerers are assumed to be off. Remanent fields could add some bending and therefore some error to the energy measurement. In the initial analysis, these are assumed to be negligibly small (contributing errors less than 10^{-4} of the dipole bends), and are not explicitly included. In recent

Table 2: Error analysis from DIMAD simulation

N	$L = 1 \text{ m}$ $\delta E/E$	$L = 2.5 \text{ m}$ $\delta E/E$
1	4.0×10^{-3}	2.3×10^{-3}
2	2.1×10^{-3}	1.0×10^{-3}
4	1.14×10^{-3}	0.44×10^{-3}
8	0.50×10^{-3}	0.23×10^{-3}

experimental tests, the remanent field contribution to the $\int B dl$ was found to be less than 5×10^{-5} .

E. Beam size effects

It was assumed that the beam size at the entrance to the arc was less than $100 \mu\text{m}$ by $10 \mu\text{rad}$. The beam size would then be less than 1.5 mm at the end of the arc, and would add a width of 10^{-4} to the final harp position uncertainty.

F. Field normalization error

An important error which was not explicitly included in simulations [3] is the error in mean magnetic field (as a function of current) in the dipoles. This absolute normalization will have to be obtained by a new set of careful absolute measurements on two or a few sample dipoles. Current measurements are absolute at only the 0.01 level. We assume this absolute calibration can be done to better than the 5×10^{-4} level and expected a 2.5×10^{-4} error level. The various error sources were combined with random error generation using the transport program DIMAD, an established, debugged transport code which is also the basic tool used in the CEBAF transport design. However, it is not optimized for error analysis and it has the disadvantage that every evaluation requires a separate run, and therefore it cannot be used to develop large-statistics random variation studies. In the analysis [3], 10 random error seeds were run and obtained error estimates of 3×10^{-4} to 6×10^{-4} . The analysis indicates that an absolute beam energy measurement at the 1.0 to 1.5×10^{-3} level is obtainable with high confidence.

IV. OPTIONS FOR THE ARC SPECTROMETER

Some variations on the measurement technique were explored. Variation of the placement of the final harp was considered. The 34.3° arc has 8 dipoles, and the final harp could be located after any one of these. Error analyses for 1, 2, 4, and 8 -dipole configurations were simulated using the same methods, and the results are summarized in Table 2.

Now a shorter configuration would permit more accurate alignment. However the dominant error is the initial missteering and the resulting displacement increases linearly with N_D , the number of dipoles. The energy-dependent displacement is proportional to the dispersion D , which increases as N_D^2 , so the energy error $\delta E/E$ decreases as $1/N_D$. Accumulation of random errors also decreases as $1/\sqrt{N_D}$. Thus, the longer arc is favored. The error analysis actually uses only three harps. The proposed configuration includes three pairs of harps: pairs at the beginning, center, and end of the arc. The harps at the center provide an energy measurement with the transport quads on and the arc tuned to the achromatic mode (360° phase advance), when the dispersion has a 2 m maximum at the center. This measurement will be calibrated by the proposed absolute energy measurement. The center harps will also provide an additional $N_D=4$ measurement in the absolute energy calibration, which will be an important consistency check. The final harp pair will also provide an independent evaluation of beam direction, and can be used as a consistency check and to reduce steering error effects by $\sqrt{2}$. The proposed method will also be capable of obtaining relative energy measurements with great accuracy. In that mode the field normalization error is inapplicable and missteering effects are reduced (by the strong focusing and 180° entrance to arc center phase advance). The dominant error should be harp misalignment and measurement uncertainties. The sum of those errors should be less than $\delta x \sim 0.2 \text{ mm}$. The resulting error in $\delta E/E$ (relative) will be on the level of $\delta x/D \sim 10^{-4}$.

V. SUMMARY

The results of the simulations and analyses discussed above indicate that it is possible to make an absolute beam energy measurement to an accuracy of about 10^{-3} . The hardware components and the optical tuning of arc are unchanged from the original beam line design. As the precision beam position probe, the upgraded CEBAF "Superharp", is developed and tested, a special alignment technique for the superharps must be carefully considered and implemented. Also at least two of the production arc dipole magnets must be mapped to obtain an absolute field integral measurement with an accuracy of 2.5×10^{-4} .

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