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BEAM ENERGY MEASUREMENT USING THE ARC BEAM LINE AS A SPECTROMETER

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Abstract

The use of the Hall C achromatic arc line as an energy analyser is proposed. It has a dispersion of 12cm/% with all the quadrupoles, sextupoles, and beam correctors switched off. The transverse position and the angle of the beam at the entrance of the arc is precisely measured by a pair of wire scanners spaced by 2.5 m, and the transverse position of the outgonig beam is measured by another pair of wire scanners at the exit of the arc. After the absolute beam energy is measured, the arc will be turned into normal achromat mode by energizing all the elements and the beam position probe located at the mid-point of the arc is used to monitor the beam energy in the operational mode. A complete error analysis shows that an absolute beam energy measurement with 10^{-3} accuracy can be achieved. Relative energy measurements at the 10^{-4} level are also obtainable.

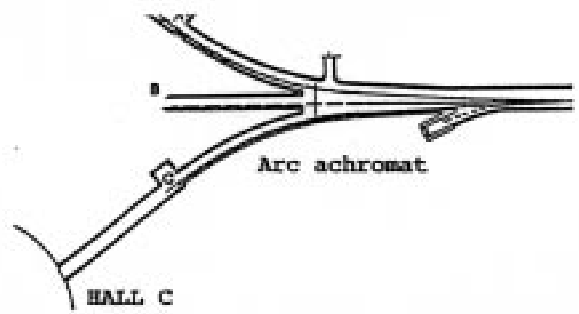

Figure 1: Hall C beam transport line

I. Introduction

The Hall C beam line is sketched in Figure 1. The arc achromat section of Hall C beam line consists of 8 dipole, 12 quads, 8 sextupole, and 8 pairs of beam correctors (vertical and horizontal), which transports the beam with second order achromaticity.

The beam energy measurement by the arc spectrometer was proposed and developed by [1], [2], and [3]. The position and the direction of the beam entering the Hall C arc line are determined at the entrance by a pair of high-resolution harps (wire scanners). The position (and direction) of the beam at the exit of the 34.3° bend (41.6 m downstream from the point of tangency) is determined by another pair of calibrated harp(s). For this procedure only the dipoles are energised. During this absolute measurement all other arc magnetic elements such as quads, sextupoles, beam correctors are off. The current in the calibrated (absolutely) bending magnets is varied to set the position to be along the central ray of the magnets in the arc. With this information the beam momentum can be determined. Thus, this method requires accurate position (and implicitly direction) measurements at the harps and an accurate determination of the magnetic field integral $\int Bdl$ as a function of current I in the arc dipoles.

The quadrupoles and sextupoles are then energised to the values required by the measured energy in the normal achromatic transportation mode. The orbit correctors are activated to center the beam on a beam position measuring device situated at the midpoint of the achromat. Under the assumption that the beam momentum is unchanged during this transition period, we can transfer the absolute momentum calibration to the achromatic mode which is very sensitive to relative shifts in the beam momentum. Variations in beam energy can then be measured as variations in beam-position at the midpoint. This achromatic mode will, also, be capable of obtaining relative energy measurements with substantially greater accuracy than the absolute mode.

II. Basic Optical Performance of the Arc Spectrometer

The beam envelope along the Hall C beam lines is shown in Figure 1. The initial beam conditions at the point of tangency are: Δ x = Δ y = 0.01 cm, Δ x' = Δ y' = 0.01 mr. For Δ p/p = 0, the solid line describes the beam envelope of the normal achromatic transportation lines,

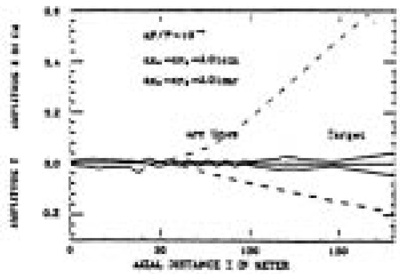

Figure 2: Beam envelope along Hall C beam lines

N	ϕ (°)	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

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

and the dashed line is for the same beam line, but switching off all quadrupoles and sextupoles in the arc section as well as in the final matching section.

For a N dipole magnet system the dispersion D $\sim N^2_{dipole} \sim L\phi/2$, where L is the total path length of central trajectory, and ϕ is the integral deflection angle of the N-dipole magnet system. The main elements of the first order matrix at the exit of N-dipole systems are listed in Table 1

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 100μm. However, with an entrance harps separation of 1m, this implies an initial direction error of 100 μrad. This 100 μrad 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 [3] analysis.

B. *Final harp location*

In the error analysis, it was assumed that a random 20 μrad missteering occurs every 10.4m (an assumed intermediate monument location), and this accumulates to obtain a dislocation at the end of the 41.6m arc. This corresponds to a mislocation of 200 μm at every arc cell. It somewhat overshoots the estimate of an rms total error of 200 μm 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 1mm, 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. It adds an rms energy error of slightly more than 10^{-3}.

D. *Quad and steering magnet effect*

In 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 the recent experimental testing, a less than 5×10^{-5} remanent field contribution to the $\int Bdl$ was found.

E. *Beam size effects*

It was assumed that the beam size at the entrance to the arc was less than 100 μm by 10 μrad. 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 is not explicitly included in [3] simulations 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. Analysis

N	L = 1 m $\delta E/E$	L = 2.5 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}

Table 2: Error analysis from DIMAD simulation

assumed this absolute calibration could 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 transport program DIMAD. DIMAD is 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 cannot be used to develop large-statistics random variation studies. In [3] analysis, 10 random error seeds were run and obtained error estimates of 3 - 6 $\times10^{-4}$. Analysis mentioned above indicates that an absolute beam energy measurement at the 1.0 to 1.5 $\times10^{-3}$ level is obtainable.

IV. Options for the Arc Spectrometer

Following the previous analysis, 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 summarised in Table 2

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 dominant error is the error in the initial direction, and that error varies inversely as the initial interharp distance. Increasing that from the initially proposed value of 1.0 m to 2.5 m (a maximum value with the existing geometry) was considered. The error analyses showed a decrease in the $N_D = 8$ $\delta E/E$ error from 0.5×10^{-3} to 0.23×10^{-3} and a decrease in $N_D = 4$ error from 1.14×10^{-3} to 0.44×10^{-3}. The current plan is to increase that interharp distance and obtain the $\sim 2\times$ reduction in error size.

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 transport quads on and the arc tuned to 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 (by $\sqrt{2}$) effects.

The proposed method will be capable of obtaining relative energy measurements with substantially greater 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 $\delta x \sim 0.2$ 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 shown above indicate that it is possible to make an absolute beam energy measurement to an accuracy of about 10^{-3} with the errors discussed above for the surveying with smoothing and assuming the interharp distance is extended from 1 m to 2.5 m. There is no need to change the hardware or the optical tuning of the achromat in the original beam line design. As the major precision beam position probes the upgrade CEBAF harp - the "Superharp" is tested and completed, a special alignment technique for the superharps must be carefully considered and implemented. 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}.

References

[1] C. Yan, R. Carlini, J. Napolitano, D. Neuffer. CEBAF-R-92-003, March 25, 1992

[2] D. Neuffer, C. Yan, R. Carlini. CEBAF-TN-92-054, November 24, 1992

[3] R.V. Servranckx. CEBAF-TN-92-044, September 29, 1992