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Beam Energy, Polarization and Current Determination using a High Resolution Chicane in Hall A

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This memo discusses the possibility of using a beam line chicane to determine the various beam parameters in a non-destructive manner. Chicanes have long been used for energy determinations at a number of laboratories. This memo discusses the size and performance criteria needed to make an absolute determination of the beam energy at the 10^{-4} level as specified in the Hall A CDR. A chicane on the entrance line is also required to perform measurements of the beam polarization using laser backscattering. It is planned to measure the asymmetry to the 1% level using this chicane. Finally synchrotron radiation in the arcs of the chicane can be used to monitor the beam current. The high resolution chicane discussed here is a very specialized form of magnetic spectrometer with alignment tolerances similar to the other high resolution spectrometers in Hall A. Presumably this device will be mounted on a rigid beam similar to the optical bench concept used for the HRS spectrometers.

The design of the chicane shown in Figure 1 is based on the following assumptions:

1) maximum beam energy of 6 GeV
2) position monitoring of the centroid of the beam to $\pm$ 100 microns
3) absolute positioning of the monitors to $\pm$ 100 microns
4) measurement of the absolute energy to 10^{-4} at 4 GeV

These criteria lead to a chicane that is approximately 20 meters long consisting of 4 rectangular magnets with a radius of curvature of 11.1 meters and a bend angle of 16 degrees. The magnetic field is 1.2 Tesla at 4 GeV/c (1.8 T at 6 GeV/c). The dispersion at the midpoint of the chicane is 1.73 meters, giving a 10^{-4} resolution in $\delta p/p$ with the above criteria for the position monitors. The current for the 4 magnets will be run in series and will be regulated at the 10^{-5} level. The magnetic field will be measured with Rawson or NMR probes in each of the magnets. In order to know the energy absolutely the magnets will have to be field mapped. The $\int B \cdot dl$ has to be determined at the 10^{-4} level. For these rectangular uniform field magnets this should pose no problem since the gap is approximately 1% of the total length of the magnet. Table 1 summarizes the parameters of the chicane magnets.

The magnets are approximately 3 meters long with a 2 cm gap and a 12 cm useful width. They weigh approximately 5 tons apiece. A sketch of the C-section magnets is shown in Figure 2. Since Poisson calculations have not yet been performed, this sketch is intended only to indicate the rough dimensions of the magnet. Table 2 gives the results of the first order transport to the center of the magnet.

Table 1

Chicane Parameters

Type	2 Symmetric dipole doublets
Configuration	Vertical bend, no net dispersion
Optical Length	20.2 m
Central Drift Length	2.0 m
Momentum Dispersion	1.73 m
Dipoles	Rectangular C-section magnets
Length	3.09 m
Gap	0.02 m
Useful Width	0.12 m
Bend Angle	16.03 °
Bend Radius	11.1 m
Magnetic Field (@ 4 GeV/c)	1.2 T
Current (@ 4 GeV/c)	19 kA-turns
Estimated Power (@ 4 GeV/c)	18 kW/dipole
Approximate O.D.	0.45 x 0.48 x 3.2 m^3
Approximate weight	5 tons

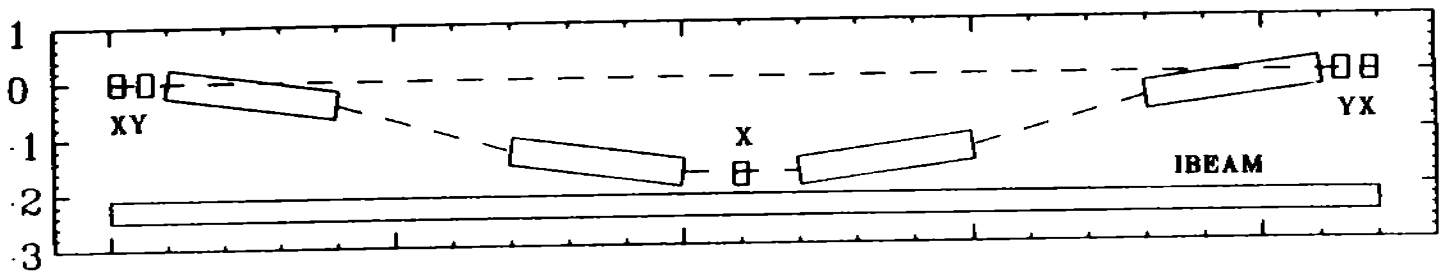
Table 2

4 GeV DD First Order Transport to Center of Chicane

(Assumes a 1 meter initial drift space)

$$\begin{pmatrix} x \\ \theta \\ y \\ \phi \\ l \\ \delta \end{pmatrix} = \begin{pmatrix} 1.00000 & 1.12194 & 0.00000 & 0.00000 & 0.00000 & 1.73466 \\ 0.00000 & 1.00000 & 0.00000 & 0.00000 & 0.00000 & 0.00000 \\ 0.00000 & 0.00000 & 0.72751 & 1.03208 & 0.00000 & 0.00000 \\ 0.00000 & 0.00000 & -0.45610 & 0.72751 & 0.00000 & 0.00000 \\ 0.00000 & 0.17347 & 0.00000 & 0.00000 & 1.00000 & 0.40794 \\ 0.00000 & 0.00000 & 0.00000 & 0.00000 & 0.00000 & 1.00000 \end{pmatrix} \cdot \begin{pmatrix} x \\ \theta \\ y \\ \phi \\ l \\ \delta \end{pmatrix}$$

Figure 1 Schematic of the beam line chicane



Chicane

(3)

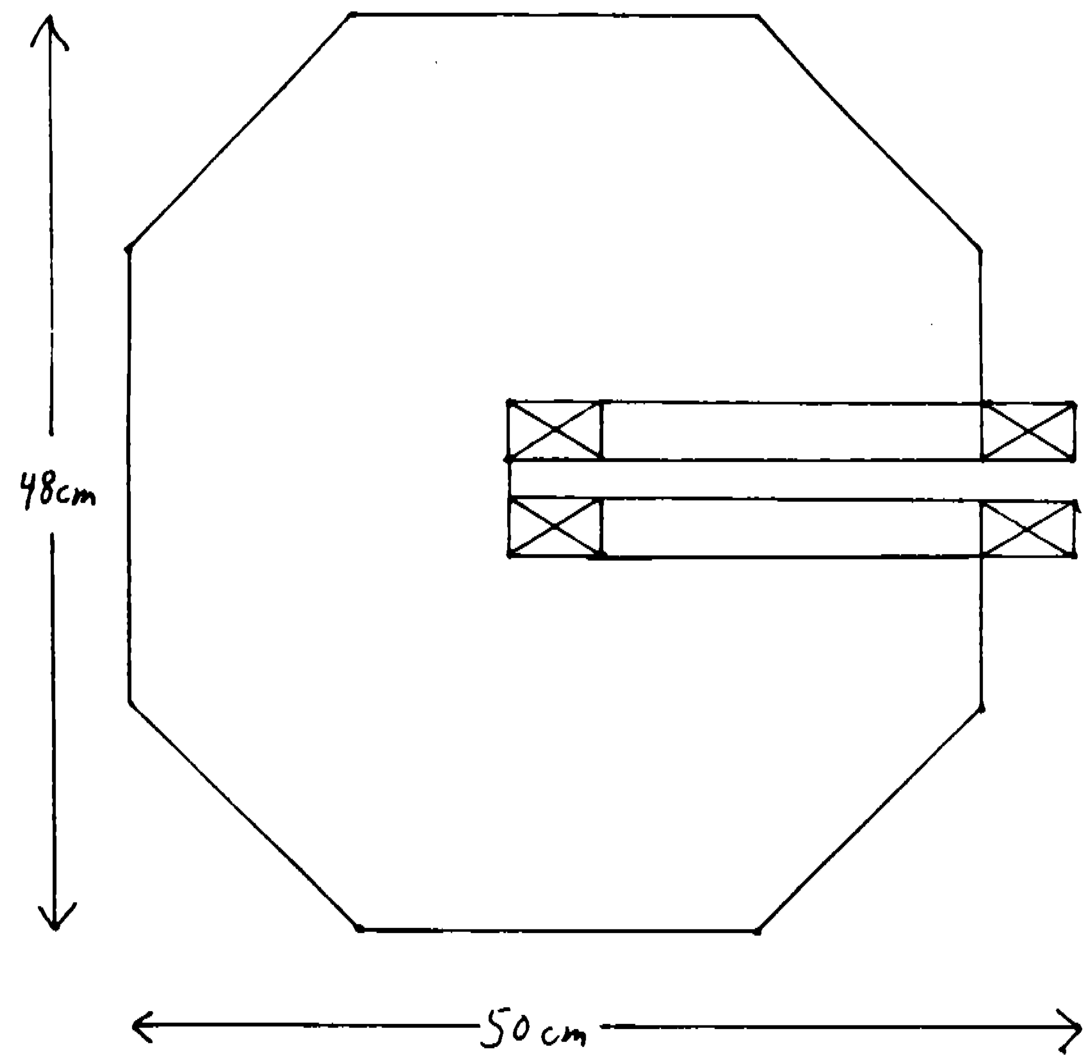


Figure 2 Approximate cross-section of chicane dipoles

1 Energy Calibration and Beam Alignment

The energy calibration and beam alignment is done using XY monitors at the entrance (X_1Y_1) and exit (X_2Y_2) of the chicane as well as an additional X monitor (X_3) at the center of the chicane. Nominally the beam centroid intercepts the center of all three monitors. The angle of the beam with respect to the center line is given by:

$$\tan\theta = \frac{X_1 - X_2}{L}$$

The vertical offset of the beam is given by :

$$V = \frac{X_1 + X_2}{2}$$

and the fractional momentum deviation is given by:

$$\frac{\Delta P}{P} = \frac{2X_3 - (X_1 + X_2)}{2D}$$

where X_i are deviations from the central values and the dispersion of the magnet $D = 1.73$ m. In principle measured deviations can be fed back to stabilize the accelerator and the beam switchyard. For example steering coils upstream of the magnets can drive X_1 and X_2 to zero with X_3 then directly determining the momentum.

Assuming a total absolute uncertainty in each of the three position measurements of $\pm$ 140 microns one can determine the absolute energy to an accuracy of $\pm 10^{-4}$, provided the magnets are understood to that level of accuracy. To achieve this level of absolute positioning the 4 dipoles must be mounted on a rigid optical bench, and the position monitors aligned to 100 microns. Assuming the design emittance of 2 x 10^{-9} m-rads, we estimate an undispersed beam spot on the order of $\pm$300 microns and we need to know the centroid to one third of that value. Temperature expansion effects are on the order of $10^{-5}/^\circ$ C. This effect can either be regulated or corrections can be made.

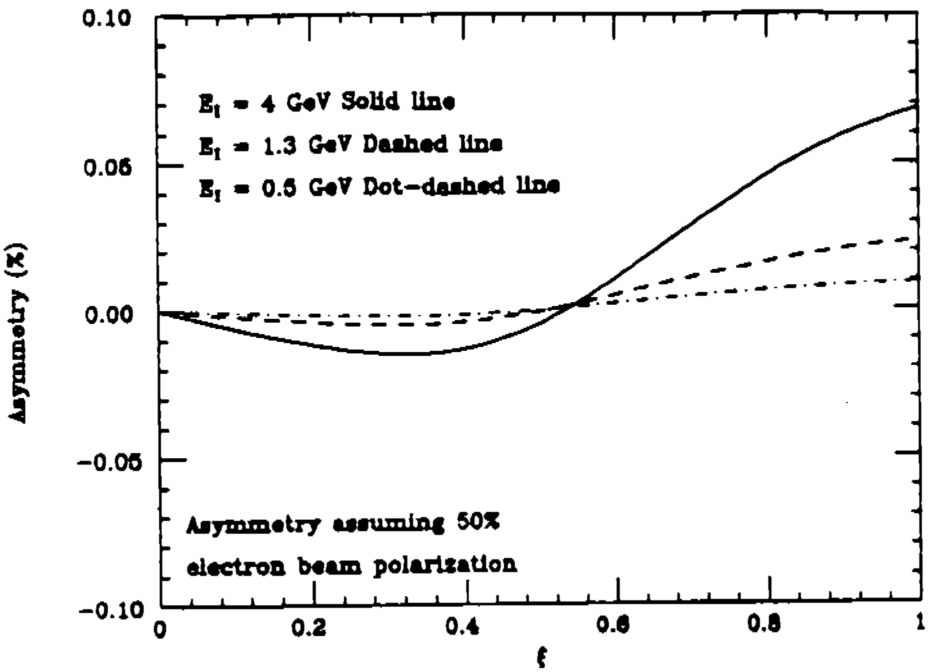
2 Beam Polarization Measurement Using Compton Scattering

The most favorable method of measuring the beam polarization at high energies (> 1 GeV) is through Compton scattering at 180°. The method requires the use of a circularly polarized laser beam and the use of a chicane as described in the Hall A CDR. The measurement of the electron beam polarization is performed by measuring the asymmetry resulting from scattering with parallel or antiparallel spin orientation of the two beams. The size of the asymmetry at high electron beam energies and the currents available make this method suitable for a high accuracy measurement.

Assuming that $E >> m >> k$, where E is the electron beam energy, m is the electron mass, and k is the energy of the incident laser photon, the energy of the backscattered photon in the lab frame is approximately:

$$k' = \frac{2k_R\gamma}{1 + 2k_R/m + \gamma^2\theta^2}$$

where $\gamma = E/m$, k_R is the energy of the laser photon in the electron rest frame, and θ is the laboratory angle of the backscatter photon relative to 180° scattering.



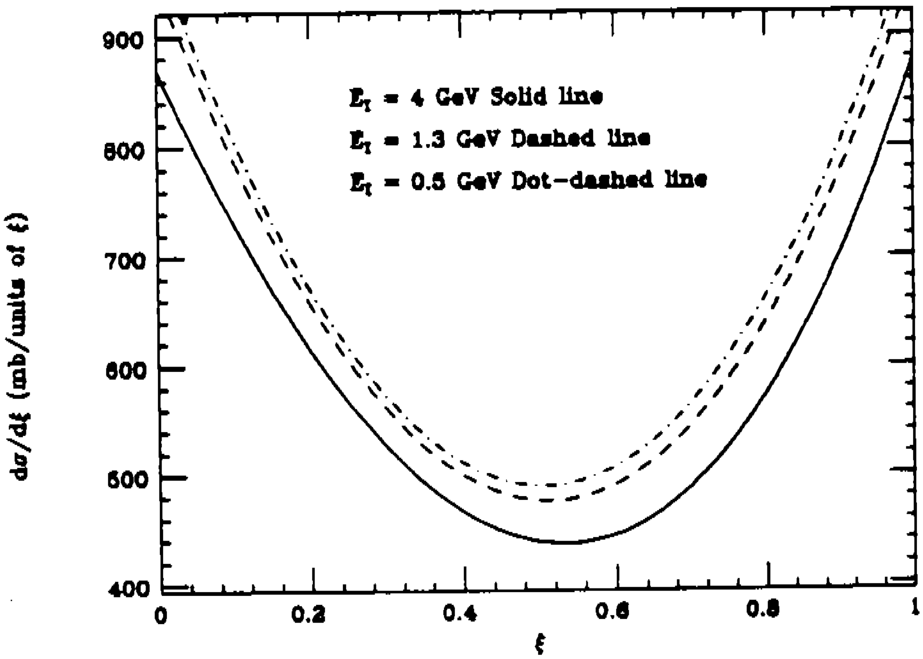


Figure 3 Longitudinal asymmetry and unpolarized cross sections for three different incident energies of the electron beam respectively $E = 4 \quad GeV$, $E = 1.3 \quad GeV$ and $E = 0.5 \quad GeV$. We assume the photon beam to be 100% polarized and the electron beam to be 50% polarized. The energy of the incident photon beam is $k = 2.41 \quad eV$

Figure 3 shows the expected asymmetry and unpolarized cross-sections for three different electron energies versus the parameter ξ defined to be the fraction of maximal energy carried by the backscattered photon. For a continuous photon beam from an Argon laser operating in the green wavelength ($\lambda = 514.5$ nm) $k = 2.41$ eV. For an electron beam of $E = 4$ GeV incident energy, the maximum energy of the backscattered photon is 514.6 MeV. The angle for which the energy drops by a factor of two is $\theta_{k'} = 1.37 \times 10^{-4}$ radians. The scattered beam is in a very narrow cone allowing easy integration over angles with a small photon detector. Alternatively one can detect the outgoing scattered electron providing one has enough dispersion in the chicane. To reduce accidentals a coincidence between the scattered electron and photon may be desired.

The rate of backscattered photons is given by:

$$N_{\gamma'} = \frac{N_e N_\gamma \sigma l}{Sc}$$

where N_e is the number of incident electrons per second, N_γ is the number of incident photons per second, σ is the integrated cross-section, l is the length of the interaction region, c is the speed of light and S is the area of the larger beam (in this case the photon beam). Table 3 lists time estimates for a 1% measurement of the asymmetry assuming 2 and 4 GeV incident beam energies and with different assumptions as to the average beam current and polarization. This table assumes an interaction length of 2 m. It also assumes a 10 W Argon laser with 100 % circularly polarized light and a 2 mm^2 spot size. The cross-section was averaged between $\xi = 0.8$ and 1.0.

Table 3

Incident energy (GeV)	average current (μA)	polarization of the beam (%)	Average Asymmetry (%)	Maximum photon Energy (MeV)	Scattered photons Rate (Hz)	Time needed (hrs)
2.	50.	50.	3.2	137.5	431.	6.3
4.	50.	50.	6.0	514.6	403.	1.9
2.	100.	80.	5.1	137.5	863.	1.2
4.	100.	80.	9.6	514.6	807.	0.4

3 Beam Current Determination Using Synchrotron Radiation

An interesting possibility is the use of synchrotron radiation to determine the current of the electron beam. The energy radiated per unit frequency interval ω is:

$$\frac{d^2 I(\omega)}{d\Omega d\omega} = \frac{\hbar\alpha}{3\pi^2}\left(\frac{\omega\rho}{c}\right)^2\left(\frac{1}{\gamma^2}+\theta^2\right)^2\left[K^2_{2/3}(\zeta) + \frac{\gamma^2\theta^2}{1+\gamma^2\theta^2}K^2_{1/3}(\zeta)\right]$$

where

$$\zeta = \frac{\omega\rho}{3c}[1/\gamma^2 + \theta^2]^{3/2}$$

ρ is the radius of curvature and the K's are modified Bessel functions. The characteristic frequency of the radiation is $\omega_c = 3\gamma^3 c/\rho$.

In the low frequency limit ($\omega << \omega_c$) the characteristic opening angle of the radiation is

$$\theta_c = (\frac{3c}{\omega\rho})^{1/3}$$

and the number of photons per second per unit frequency interval averaged over detector acceptance is

$$\frac{dN(\omega)}{d\omega} \simeq 0.517\frac{\alpha}{\omega}(\frac{\omega\rho}{c})^{1/3}\frac{l}{\rho}N_e$$

where l is the arc length seen by the photon detector and N_e is the number of electrons per second. For visible light (400-700 nm) one can expect to see $\sim 10^{10}$ photons per second per microamp beam current per cm of arc length, with the results nearly independent of the beam energy for CEBAF energies.