Requirements on Beam Properties for Qweak

The following are estimates of sensitivities to beam parameters (position, size, angle on target, energy, transverse polarization) based on the January 2008 version of the Qweak collimator. Results are for electrons of energy 1.165 GeV, BFIL = 1.04 (QTOR field 4% above nominal value) and a cut on Cerenkov bar position from 319 to 337 cm in radius and ±100 cm along its length. The Cerenkov bars are 570 cm downstream from the center of the QTOR magnet. A flat detector response is assumed. A summary of the basic beam requirements is shown in Table 1 (below). The helicity correlated beam property requirements shown below are integrated over the whole measurement. Note: The beam halo requirements for the new Hall C Compton polarimeter and to some extent for the Qweak apparatus must be determined experimentally during the spring 2010 commissioning run. A detailed discussion of these requirements and implications for the measurement is also provided.

Table 1 (Summary)

Qweak "Commissioning" Beam Requirements

Parameter	Max. DC value	Max. run-averaged - helicity-correlated value (~2544 hours)
Beam intensity	180 μA (150 μA nominal)	$A_Q < 10^{-7}$
Beam energy	$\Delta E / E \leq 10^{-3}$ (Q^2 measurement)	$\Delta E / E \leq 10^{-9}$ 3.5 nm@35 mm/%
Beam position	+- 0.5 mm	$<\delta x> < 2$ nm
Beam angle	$\theta_0 = 60$ μrad	$<\delta\theta> < 30$ $n$rad
Beam diameter	4 - 5 mm rastered (100-300 μm selectable unrastered)	$<\delta\sigma> < 2$ nm
Residual Transverse Pol.	$<\delta P_y> = 0$ (max excursions < 4%)	requires retune when $\delta P_y > 4\%$
Beam Trip Rate	NA	< 10 / hour
Beam Halo	Parity Quality (<10^{-6} integrated > 2 mm from from edge of 5 mm x 5mm rastered beam) Note: Compton polarimeter halo requirement will be different and will be determined during commissioning run)	
Tracking Run Beam Intensity	100 pA to 10 nA selectable	
Helicity Reversal Reversal Rate	1 ms pseudo random quad pattern with ~ 80μs settling time & several days at other rates	
Polarization	> 85% average (require "100%" longitudinal tune to Hall C)	

Position and Size Modulation

The electrons are directed uniformly onto the central 5 mm x 5 mm area of the target. Asymmetries are calculated when the electron beam moves on helicity flip as
$x_\pm = x_0 \pm \delta x$, and $y_\pm = y_0 \pm \delta y$. The rastered beam covers $x_0 \pm \Delta x$ in x and $y_0 \pm \Delta y$ in y. The size parameters Δx and Δy may change by $\pm\delta_{\Delta x}$ and $\pm\delta_{\Delta y}$ on helicity flip. Table 2 shows results for a single Cerenkov bar, for pairs of diametrically opposite bars, and for the Cerenkov array as a whole. The reference position for the single Cerenkov bar is with its center in the x-z plane and the bar parallel to the y-axis. Best fits to event rate as a function of the position (x, y) of a beam element on target are shown. Single Cerenkov bars show a large sensitivity to position modulation that should vary in a sinusoidal pattern around the detector array. For a perfect Cerenkov array, sensitivities are reduced drastically by considering diametrically opposite pairs of bars. A small linear term reappears if the pair of bars is shifted left or right. The additional false asymmetry becomes about 9 x 10^{-10}, independent of x_0, when the bars are shifted by 1 cm and
$\delta x = \pm 2$ nm. The false asymmetry goes as the square of the displacement of the bars. A similar effect would be seen if the QTOR field is about 1% high for one bar of the pair and 1% low for the other.

For the "worst case" distortion of the Cerenkov array as a whole, in which bars on one side of the array are moved inward and bars on the opposite side are moved outward, the false asymmetry picks up a linear term leading to a false asymmetry of 4.3 x 10^{-10} when the bars are displaced by 1 cm and $\delta x = \pm 2$ nm. Size modulation
(with $\Delta x_\pm = \Delta x \pm \delta_{\Delta x}$, $\Delta y_\pm = \Delta y \pm \delta_{\Delta y}$) introduces an additional false asymmetry. For a beam rastered to 4 mm x 4 mm ($\Delta x = \Delta y = 2$ mm), the false asymmetry in a single bar or a pair of bars is about 5.9 x10^{-10} when $\delta_{\Delta x} = -\delta_{\Delta y} = \pm 2$ nm (that is, when the beam expands in diameter by 4 nm in x while contracting in diameter by 4 nm in y). If the beam expands and contracts uniformly, the false asymmetry is an order of magnitude smaller. Because of the symmetry of the whole array, the false asymmetry is greatest for the whole array when the beam expands and contracts uniformly. The asymmetry is about 1.7 x 10^{-10} when by $\delta_{\Delta x} = \delta_{\Delta y} = \pm 2$ nm.

Direction Modulation

Table 2 shows results for a beam rastered to 4 mm x 4 mm that is pivoted about the center of the target, changing direction on helicity flip as $\theta_\pm = \theta_0 \pm \delta\theta$. The beam travels toward the center of the target in the x-z plane at an angle θ_0 chosen randomly between $\pm 0.2^0$ relative to the z-axis. For a single bar, the dominant effect is a linear term proportional to $\delta\theta$, giving a false asymmetry of 9.5 x 10^{-7} for $\delta\theta = \pm 30$ nrad. The linear term cancels for a pair of diametrically opposite bars, leaving an asymmetry going as
(θ_0 x $\delta\theta$) and of magnitude 1.7 x10^{-9} when $\delta\theta = \pm 30$ nrad and $\theta_0 = 60$ μrad. The symmetry of the whole Cerenkov array reduces the error further to 5.4 x 10^{-10} for the same beam parameters.

Transverse Polarization

If the beam has a transverse polarization, P_y, a parity-allowed asymmetry $P_y A_y \cos\varphi$ can be produced in single Cerenkov bars around the array [$A_y \sim (5\text{-}10) \times 10^{-6}$]. For a perfect array and the beam precisely on axis, the false asymmetry cancels when averaged over all bars. Table 2 shows the variation of rate with position (x,y) of beam on target, together with the ($1 \pm P_y A_y \cos\varphi$) variation due to a transverse beam polarization. False asymmetries are estimated for $P_y = 0.005$, $A_y = 10^{-5}$, x = 0.1 cm, a = 0.122 cm^{-1}. A false asymmetry results also if the beam has a transverse polarization and is not parallel with the z-axis. Table 2 shows the variation of rate with a fixed angle θ of beam on target combined with the polarization effect.

Energy Modulation

When the beam energy changes on helicity flip, $E_\pm = E_0 \pm \delta E$, the event rate changes and a false asymmetry is seen. The effect is due not only to the change of e-p scattering cross-section, but also to the electrons being swept across the Cerenkov bars. There is little sensitivity to beam energy at 1.165 GeV. Without a cut on bar position, the event rate varies as $R \sim 1 + aE$, with a = -0.57 GeV^{-1}, leading to a false asymmetry of $a\,\delta E$ when the beam energy changes by $\pm\delta E$ on helicity flip. The false asymmetry is 6×10^{-10} when $\delta E/E = \pm 10^{-9}$.

Table 2

Updated Requirements on Beam Properties for Qweak

Estimated false asymmetries in units of 10^{-10}

Modulation	Conditions	Single Bar	Pair of Bars	Whole Array
Position	$x_0 = 1$ mm, $\delta x = \pm 2$ nm	250	3.8	0.8
	$\theta_0 = 60$ μrad			
Position	$x_0 = 1$ mm, $\delta x = \pm 2$ nm	250	9.2	4.2
+ distorted array	$\theta_0 = 60$ μrad, $x_{bar} = 1$ cm			
Correlated	$x_0 = 1$ mm, $\delta x = \pm 2$ nm	-	-	1.3
position & angle	on axis at raster			
Correlated	$x_0 = 1$ mm, $\delta x = \pm 2$ nm	-	-	4.3
position & angle	on axis at raster			
+ distorted array	$x_{bar} = 1$ cm			
Beam size	$\Delta x = \Delta y = 2$ mm,	5.9	4.3	0.7
	$\delta_{\Delta x} = \pm\delta_{\Delta y} = \pm 2$ nm	$\delta_{\Delta y} = -\delta_{\Delta x}$		$\delta_{\Delta y} = \delta_{\Delta x}$
Correlated	$\Delta x = \Delta y = 2$ mm,	-	-	1.7
position & angle	$\delta_{\Delta x} = \delta_{\Delta y} = \pm 2$ nm			$\delta_{\Delta y} = \delta_{\Delta x}$
	on axis at raster			
Direction	$\theta_0 = 60$ μrad, $\delta\theta = \pm 30$ nrad	9500	17(165)	5.4(55)
			$x_0 = 0(1$ mm$)$	
Direction	$\theta_0 = 60$ μrad, $\delta\theta = \pm 30$ nrad	9500	130(280)	74(125)
+ distorted array	$x_{bar} = 1$ cm		$x_0 = 0(1$ mm$)$	
Transverse	$P_y = 0.04, A_y = 10^{-5}$			
polarization	$x_0 = 1$ mm	$4000 \cos\phi$	$48 \cos\phi$	24
+ distorted array	$x_{bar} = 1$ cm	$4000 \cos\phi$	$110 \cos\phi$	60
	$\theta_0 = 60$ μrad	$4000 \cos\phi$	$7.4 \cos\phi$	3.6
+ distorted array	$x_{bar} = 1$ cm	$4000 \cos\phi$	$70 \cos\phi$	42
Beam energy	$\delta E/E = 10^{-9}$	< 6	< 6	< 6

Notes

1) The position of the beam at the target as a function of helicity state is:

$$x^{\pm} = x_0 \pm \delta x, \text{ and } y^{\pm} = y_0 \pm \delta y$$

2) The extent of the raster at the target is:

$$x_0 - \Delta x \text{ to } x_0 + \Delta x \text{ and } y_0 - \Delta y \text{ to } y_0 + \Delta y,$$

so the width of the beam is $2\Delta x \times 2\Delta y$. Nominally, $\Delta x = \Delta y = 2$ mm.

3) Δx and Δy can change by $\pm\delta_{\Delta x}$, $\pm\delta_{\Delta y}$ on helicity flip, a total of $4\delta_{\Delta x}$ and $4\delta_{\Delta y}$ in width.