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Beam Profile Monitors for the AGS

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Instruments for measuring beam size have been built for use at various accelerators.[1,2,3,4,5] Some notes are given below on methods that seem promising for the AGS. In each case, typical numerical examples are given.

1. Segmented Secondary Emission Chamber in the Fast Extracted Beam

Two foil-strip signal planes and three foil bias planes would add up to 0.02% interaction lengths of material if made of 10 micron aluminum. They could be left permanently in the beam. A vacuum of better than 10^{-5} Torr is needed and an arrangement without windows that communicates with the beam line vacuum is possible. The bias field must be at least 1 kV/cm to overcome space charge forces. The bias foils would also be part of the shielding that is needed against electrostatic coupling to the beam.

The advantages of such a detector are that it could be put in a dispersion-free location where no momentum spread correction is needed, and that it includes any effects of fast extraction. The disadvantages are that it does not provide beam size measurements as a function of energy during acceleration and that the fast extraction equipment is required.

If we integrate over the entire beam, then the electronics are particularly simple. If we want to measure the profile of a single bunch, then care with electrostatic shielding is needed and special electronics are required.

For integrating the entire beam, the signal size is:

$$V = \frac{2}{n_{el}} N e \varepsilon_s / C = 1.1 \text{ V}$$

where

n_{el} = number of elements $\simeq$ effective beam width/strip width = 30

N = number of protons in beam = 1×10^{13}

e = 1.6×10^{-19} C

ε_s = secondary emission coefficient = 0.02

C = integrating capacitance = 2000 pF

For measuring a single bunch separately, either special integrators must be located near the detector in the beam line enclosure, or, with the electronics outside the enclosure, the detector must drive terminated cables, and the cables must be well matched to prevent cross talk between bunches. With the cables the signal from secondary emission is:

$$V_s = \frac{1}{h} \frac{2}{n_{el}} N e \varepsilon_s R/\Delta t = 0.9 \text{ V}$$

where

h = harmonic number = 12

R = cable impedance = 100 Ω

Δt = bunch width = 20 nsec

At the same time, there will be a spurious signal that is capacitively coupled from the beam potential. This signal can be integrated out provided it is not too large. The size of the capacitively coupled signal is:

$$V_c = \frac{1}{h} N e \frac{RC'}{C\Delta t}$$

where

C = capacitance from beam to ground $\simeq$ 200 pF

C' = capacitance from beam to pickup wire

In order to have $V_c = V_s$, it is necessary to have C' = 0.3 pF, which requires careful shielding.

2. Ionization Profile Monitor

The electrons that are produced by collisions of the circulating beam with residual gas can be extracted onto a parallel strip detector and the resulting charge can be digitized by multichannel integrators to give the beam profile. Separate detectors for the horizontal and vertical planes are needed, located in β^H_{max} and β^V_{max} straight sections respectively. An operating pressure of 10^{-6} Torr can be provided by a simple controlled leak, with local pumping to isolate the rest of the ring vacuum.

2.1 Signal Size

The amount of current collected is

$$I = \frac{1}{n_{el}} \, Ne \, f_r \frac{dE}{dX} \frac{1}{E_i} \frac{P}{760} \rho \ell = 17 \times 10^{-9} \mathrm{A}$$

where

f_r = rotation frequency = 3.7×10^5 sec^{-1}

$\frac{dE}{dX}$ = energy loss in Nitrogen = 1.8×10^6 eV/g/cm^2

E_i = energy loss per ion pair = 35 eV

P = pressure in Torr = 1×10^{-6} Torr

ρ = density of Nitrogen at 1 atm = 1.3×10^{-3} g/cm^3

ℓ = collector length = 10 cm

The peak current is about four orders of magnitude lower than for the segmented SEC, and detection of a single bunch will be difficult although perhaps not impossible.

On the other hand, it will be straightforward to digitize the signals when integrated over a reasonable sampling time. The charge per channel will be 170 pC for 10 msec sampling time, for example.

2.2 Beam Size, Charge and Electric Field

Approximate the beam at 30 GeV and full intensity by a round Gaussian charge distribution

$$\rho(r) = \frac{dQ/d\ell}{2\pi\sigma^2} e^{-r^2/2\sigma^2}$$

with

σ = standard deviation of beam size = $\sqrt{\beta\varepsilon}$ = 0.17 cm

β = betatron function = β_{av} = 15 m

ε = rms emittance = 0.2×10^{-6} m-rad

The charge density is

$$\frac{dQ}{d\ell} = \frac{1}{h}\ \frac{Ne}{c\Delta t} = 2.2 \times 10^{-10} \text{ coul/cm}$$

with

$$c = 3 \times 10^{10} \text{ cm/sec}$$

The self-field of the beam is

$$E_b(r) = \frac{dQ/d\ell}{2\pi\varepsilon_o r}\ (1 - e^{-r^2/2\sigma^2})$$

where

$$\varepsilon_o = 8.85 \times 10^{-14} \text{ F/cm}$$

The peak field is

$$E_b^{max} = E_b(1.6\ \sigma) = \frac{0.45\ dQ/d\ell}{2\pi\varepsilon_o\sigma} = 1000 \text{ V/cm}$$

2.3 Profile Distortion by Space Charge

The extraction field must be large compared to E_b^{max}. Otherwise, by the time an electron has been extracted from the vicinity of the beam's electric field influence, it would be displaced transversely by an amount comparable to or greater than the beam size. The beam size information would then be hopelessly distorted. For example, the IBS,[2] with typical extraction fields of a few hundred V/cm, is not suitable for profile measurements of the bunched AGS beam. Let us then assume

E_e = extraction electric field = 5000 V/cm = 5×10^{10} erg coul^{-1} cm^{-1}.

This field could be produced, for example, by 50 kV dc applied across 10 cm. Opposite fields upstream and downstream would cancel the effect on the beam. The maximum transverse displacement of an electron that has been extracted from the beam region (but is still a distance of a few times σ from the beam) is

$$x_\perp \simeq \frac{E_b^{max}}{E_e}\ \sigma = 0.03 \text{ cm}$$

The resulting distortion of measured beam width, added in quadrature, will be only a few percent of σ.

In addition to its transverse displacement, the electron will have received a transverse velocity of

$$v_\perp \simeq \frac{E_b^{max}}{E_e} \sqrt{2(e/m)E_e\sigma} = 3.5 \times 10^8 \text{ cm/sec}$$

where

$$m = 9.1 \times 10^{-28} \text{ g}$$

In the absence of a focussing magnetic field, this transverse velocity would lead to an unacceptable broadening of the beam profile by the time the electron reaches the collector. Let

$$L = \text{distance to collector} = 5 \text{ cm}$$

then

$$t = \text{time to collect } \sqrt{2L/[(e/m\ E_e)]} = 1.1 \times 10^{-9} \text{ sec}$$

The amplitude error at the collector would then be $v_\perp t = 0.4$ cm.

2.4 Magnetic Focussing

The error due to transverse velocity can be largely eliminated by the focussing effect of a uniform magnetic field. Assume a field

$$B = 330 \text{ Gauss} = 0.03 \text{ T.}$$

As discussed below, the best choice is to have $\vec{B}$ parallel to $\vec{E}$ and hence transverse to the beam. Such a field can be provided by a small C-magnet made of steel plates with an air-cooled coil. Identical magnets with the half the length and opposite field would be used upstream and downstream to cancel all effects on the beam, aside from a local orbit bump of approximately 1 mm at injection.

With this field the cyclotron frequency is

$$\omega = \frac{e}{m[kg]} B = 5.8 \times 10^9 \text{ sec}^{-1}$$

The transverse velocity $v_\perp$ will now lead only to an oscillatory motion with half-amplitude $v_\perp/\omega = 0.06$ cm. Even the small distortion resulting from this motion will be largely eliminated since the fields are chosen to make $\omega t = 2\pi$ so that there will be one full oscillation in going from the beam to the collector.

The magnetic field could be either parallel or transverse to the electric field. For the $\vec{E} \perp \vec{B}$ case we have cycloidal motion perpendicular to both $\vec{E}$ and $\vec{B}$ with velocity

$$v = \frac{E\ [V/m]}{B} = 1.5 \times 10^7 \text{ m/sec} = 1.5 \times 10^9 \text{ cm/sec}$$

and half amplitude

$$v/\omega = 0.26 \text{ cm}$$

The transit time is

$$t = L/v = 3.3 \times 10^{-9} \text{ sec}$$

or three times longer than in the $\vec{E} \parallel \vec{B}$ case. It is particularly important to have an integral number of cyclotron oscillations in this case in order to cancel errors from the cycloidal motion, and extra requirements are thereby put on field uniformity. A further disadvantage over the $\vec{E} \parallel \vec{B}$ case is that the electric field would have to be applied along the scan direction. For a detector at a β_{max} location, this means 50 percent larger plate spacing and hence 50 percent more voltage.

A minor advantage of the $\vec{E} \perp \vec{B}$ case is that, with a solenoidal rather than transverse field, no field compensation is needed. On balance the $\vec{E} \parallel \vec{B}$ case, with the electrons spiraling along the electric field direction, seems preferable.

3. Wire Scanner

Particles coming from interactions of a fine wire that is scanned through the internal AGS beam can be detected to give profile information. The simplest mechanical arrangement is motion at the end of an arm driven by a continuously running motor. A 1500 rpm motor would give one scan per 40 msec, which is convenient for mapping out the beam size during acceleration. Provision has to be made for synchronizing the rotation to the AGS cycle and providing a gate for the electronics, and also for ensuring that the wire always parks outside the beam when the motor is shut off. A limit on the scan speed is that the displacement should not exceed 0.01 cm per beam revolution, leading to a 25 cm radius and

$$v = \text{scan speed} = 4000 \text{ cm/sec.}$$

The wire would be carbon because of its low Z, high melting point and availability in fine fibers.

3.1 Effect on Beam

The amount of material in the beam is 8×10^{-9} g/cm^2, an amount equivalent to the residual gas if the average AGS pressure were 6×10^{-8} Torr. The increase in rms emittance for a single pass of the wire through the beam is

$$d\varepsilon = \beta \left(\frac{.015}{p}\right)^2 \frac{E}{p} \frac{\pi}{8} \frac{d^2 f_r}{v\, L_{rad}}$$

where

$\beta = \beta_{max} = 22$ m

E = total energy in GeV

p = momentum in GeV/c

d = wire diameter $= 1.0 \times 10^{-3}$ cm

L_{rad} = radiation length in Carbon = 27.5 cm

The fractional increase in emittance per scan is then

$$\left.\frac{d\varepsilon}{\varepsilon}\right|_{1\ \text{scan}} = 0.11\% \times \frac{E}{p^2}$$

For 25 scans starting at injection, the total effect is

$$\left.\frac{d\varepsilon}{\varepsilon}\right|_{\text{acceleration cycle}} = 0.5\%$$

The wire scanner should therefore be a non-destructive monitor

3.2 Heating of the Wire

The worst case for temperature rise at is 30 GeV. The heating depends on the beam size transverse to the scan direction,

$$h_{eff} = \sqrt{2\pi\ \beta_{min}\varepsilon} = 0.37\ \text{cm}$$

The temperature rise for a single pass through the beam is

$$\Delta T = N\, f_r\, \frac{1}{h_{eff} v}\, \frac{dE}{dX}\, \frac{1}{C} = 570°K$$

where

$\frac{dE}{dX}$ = energy loss $= 1.8 \times 10^{6}$ eV/(g/cm^2) = 2.9×10^{-6} erg/(g/cm^2)

C = specific heat of Carbon $= 1.3 \times 10^{7}$ erg g^{-1} °K^{-1} at 300°C.

The spread of the heat pulse during one pass is of order

$$\Delta x \simeq \pi \left(\frac{Kt}{C\rho} \right)^{1/2} = 0.09\ \text{cm}$$

where

K = thermal conductivity of Carbon $= 4.5 \times 10^{5}$ erg sec^{-1} °K^{-1} cm^{-1}

t = time between scans = 0.04 sec

ρ = density of Carbon = 1.55 g/cm^2

Therefore, conduction is negligible and cooling is by radiation.

When equilibrium is reached, the peak temperature will be approximately

$$T \simeq \left(\frac{C \rho d \Delta T}{4\varepsilon_b \sigma t} \right)^{1/4} + \frac{1}{2} \Delta T = 1370°K$$

where

ε_b = emissivity of Carbon = 0.9

σ = Stefan-Boltzman constant = 5.67×10^{-5} erg sec^{-1} cm^{-2} $°K^{-4}$

This temperature is well below the melting temperature of Carbon, 3900°K.

4. Conclusion

In order to be able to measure, monitor and improve the transverse AGS emittance, it seems both practical and desirable to build a Segmented S.E.C. in the Fast Beam, and either an Ionization Profile Monitor or a Wire Scanner in the Ring.

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