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Electron Trappings In RHIC From A Debunched Proton Beam

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RHIC-PG-52

Electron Trappings in RHIC from a Debunched Proton Beam

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Ion Trapping / Electron Trapping

Proton Beam Completely Debunched

Gas Composition as derived in RHIC-PG-51

Densities:

Molecules	Z	A	warm 25%	cold 75%
H_2	2	~~2~~	$2.1 \times 10^7\ cm^{-3}$	$2.3 \times 10^7\ cm^{-3}$
He	2	4	–	$2.3 \times 10^7\ cm^{-3}$
CO	14	28	$2.1 \times 10^7\ cm^{-3}$	–

Ionization cross-section σ_i

$$\sigma_i = 1.8 \times 10^{-19} Z_i \ cm^2$$

Ionization Rate for the ith specie per proton

$$\frac{dn_i}{dt} = c\,\sigma_i\,n_i \qquad (\beta = 1)$$

ions	ionization rate
H_2^+	0.243 s^{-1}/proton
He^+	0.186
CO^+	0.397
electrons	0.826 s^{-1}/proton

The ions (positively charged) are rejected by the potential barrier of the proton beam.

The electrons could be trapped

Average energy of the electrons at production

$1/40$ eV

which corresponds to a velocity

$$v_e \simeq 10^7 \text{ cm/sec}$$

To "clear" the electrons one can create one or several gaps in the beam — These gaps though are to be no less than 300 ~~nsec~~ nsec if the electrons have to reach a wall 3 cm away with the velocity given above —

Assume the proton beam has a uniform density distribution with elliptical cross-section of semi-axis σ_x, σ_z —

I, beam current $= Ne f_{rev} = 57\times10^{12}\times1.6\times10^{-19}\times78.2\times10^{3}$

$= 0.71$ Ampère

Electric Field produced by the beam

$$E_{x,z} = \frac{(120\,\mathrm{ohm})\, I_{amp}}{\sigma_x + \sigma_z}\,\frac{(x,z)}{\sigma_{x,z}} \qquad \mathrm{Volt/m}$$

The voltage distribution is

$$V = \frac{43\ \mathrm{Volt}}{\sigma_x + \sigma_z}\left(\frac{x^2}{\sigma_x} + \frac{z^2}{\sigma_z}\right)$$

The potential barrier depth is calculated by setting $x = \sigma_x$ and $z = \sigma_z$, and that is

$$\boxed{\Delta V = 43 \text{ Volts}}$$

Oscillation Frequency of the Trapped Electrons

$$\omega^2_{x,z} = \frac{(120 \text{ ohm})\, I\, e c^2}{m_e c^2\, \sigma_{x,z} (\sigma_x + \sigma_z)}$$

where $m_e c^2 = 0.5$ MeV and $\sigma_{x,z}$ is in meter

$\langle \sigma_{x,z} (\sigma_x + \sigma_z) \rangle \simeq 2\sigma^2$, $\sigma \sim 4$ mm

As a result

$$\boxed{\omega_{x,z} \simeq 700 \text{ MHz}}$$

Betatron Tune Depression

$$\Delta\nu_{x,z} = \frac{e}{4\pi m\beta^2\gamma c^2}\oint ds\ \beta_{x,z}(s)\,\frac{\partial E^{\text{electrons}}_{x,s}(s)}{\partial x,z}$$

E^{electron} is the electric field generated by the electrons in the background

$$\frac{\partial E^{\text{electron}}_{x,z}}{\partial x,z} = \eta\,\frac{(120\ \text{ohm})\,I}{\sigma_{x,z}(\sigma_x+\sigma_z)} = \frac{86\,\eta}{\sigma_{x,z}(\sigma_x+\sigma_z)}$$

η, charge neutralization coefficient caused by the electrons

We have

$$\Delta\nu_{x,z} = \frac{120\,eI}{4\pi m_0\beta^2\gamma c^2}\oint\frac{\eta(s)\,\beta_{x,z}(s)}{\sigma_{x,z}(\sigma_x+\sigma_z)}\,ds$$

$$= \frac{120\,Ie}{8\pi mc^2\beta^2\gamma}\,\bar{\eta}\int\frac{\beta(s)}{\sigma^2(s)}\,ds$$

or

$$\Delta\nu = \frac{120\, I e}{4\pi m c^2 \beta^2 \gamma} \frac{\bar{\eta}}{\varepsilon} 2\pi R$$

with

$$\varepsilon = \frac{2\sigma^2}{\beta} = 0.06 \text{ mm}\cdot\text{mrad}$$

$R = 610.2$ m
$\gamma = 100$
$mc^2 = 0.9383$ GeV

We get

$$\Delta\nu = 4.64\, \bar{\eta}$$

It is safe to keep $\Delta\nu \lesssim 0.0025$, therefore one requires

$$\boxed{\bar{\eta} \lesssim 0.0005}$$

Removal of the Electrons

Electrons have a longitudinal drift
After a time t they have travelled a distance

$$\ell = v_e t$$

where $v_e \sim 1 \times 10^7$ cm/sec

We assume that after this distance they are removed. We take

$$t = \eta \tau_e$$

$\tau_e = 1.21$ sec is the production time per proton

With $\eta = 0.0005$

$$\underline{\underline{\ell = 6{,}050 \text{ m}}}$$

Drift in a Dipole (B_z)

This occurs at velocity v_D

$$v_D = \frac{E_x}{B_z} \frac{\omega_L^2}{\omega_L^2 + \omega_x^2} = x \frac{\omega_L \omega_x^2}{\omega_L^2 + \omega_x^2}$$

$$\omega_L = \frac{e B_z}{m_e}$$, $2\pi \times$ Larmor frequency

$$= 5.6 \times 10^{11} \text{ Hz}$$

Therefore $\omega_L \gg \omega$, and

$$v_D = a \frac{\omega_x^2}{\omega_L} = 3.5 \times 10^5 \text{ cm/sec}$$

Drift in a Quadrupole with Gradiant B'

$$V_Q = x \frac{\omega_Q \, \omega_x^2}{\omega_Q^2 + \omega_x^2}$$

where

$$\omega_Q^2 = \frac{1}{2} \left(\frac{e B'}{mc} \right)^2 \sigma^2$$

with $B' = 550$ KG/m and $\sigma = 4$ mm

$$\omega_Q = 2.9 \times 10^{10} \text{ Hz}$$

Therefore $\omega_Q \gg \omega_x$ and

$$V_Q = \sigma \frac{\omega_x^2}{\omega_Q} \cong 6.8 \times 10^6 \text{ cm/sec}$$

In ~~the~~ conclusion the drift velocity is quite smaller in the dipoles. The calculations of page 7 to clear the electrons have to be repeated by taking

$$v_e = v_D \sim 3.5 \times 10^5 \text{ cm/sec}$$

We obtain then

$$\ell = 212 \text{ m}$$

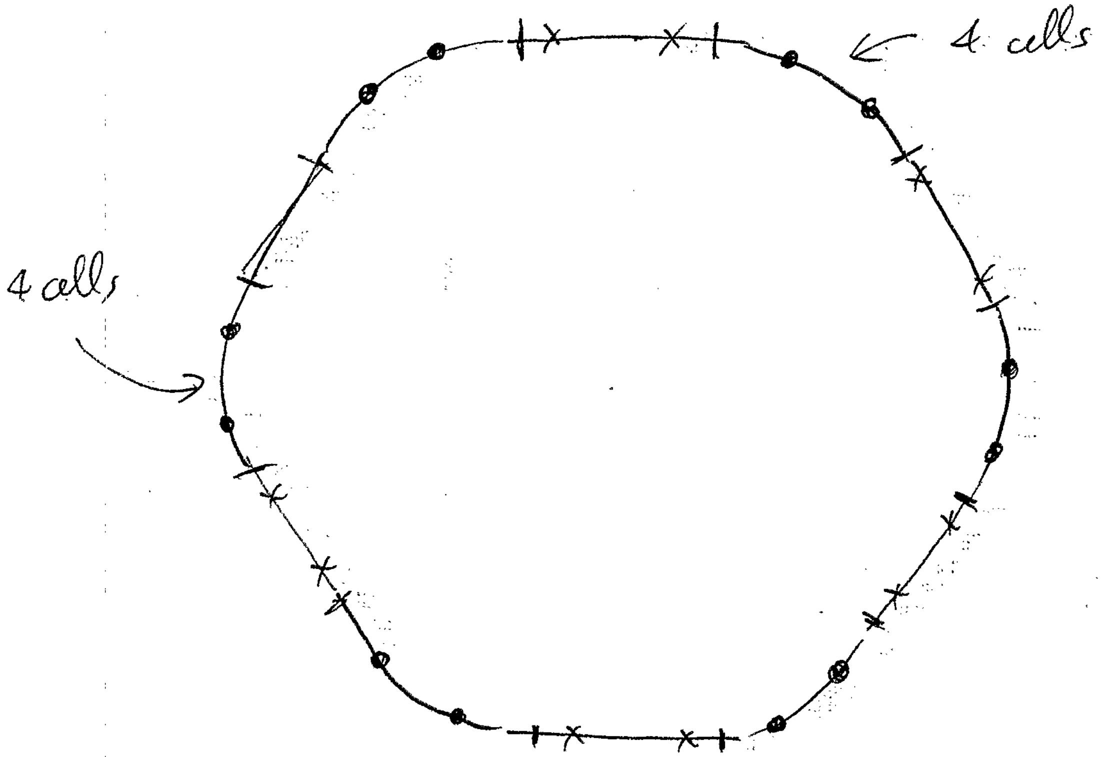
This corresponds to the length traversed in the dipoles: it is about 10 dipoles, that is 5 cells.

<u>Solution</u>: install pairs of cleaning electrodes in the warm sections at the beginning and at the end of each long straight section.
Install also pairs of cleaning electrodes in the arcs equally spaced 4 full cells apart. So there are in total 24 pairs, 12 in cold sections and 12 in warm sections (see figure next page).
Take a gap separation $\underline{d}$ flush with the vacuum chamber and ~~the~~ a length $L = d$.

To sweep the electrons away the following voltage is required

$$V_c = m_e c^2 \left(\frac{d V_e}{c L} \right)^2$$

which is quite negligible compared to $\Delta V = 43$ Volt. It is quite safe to take $V_c \approx 100$ Volt.



● Clearing Electrodes in cold section

× " " in warm section