INCREASE OF BEAM INTENSITY

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ABSTRACT

A method of particle injection into ring accelerators (cyclotrons, synchrotrons) with strong focusing is given and analytically substantiated. The given method ensures about three fold increase as compared with existing ones.

The maximum mean beam current in ring accelerators (cyclotrons, synchrotrons) determined by the decrease in free vertical oscillation frequency under the influence of space charge is calculated from the formula[1,2]

$$I = 3.2 \times 10^{-19} \frac{\pi Q_{zo} \Delta Q_z \beta^2 \gamma^3 a^2 BmFf}{Rr_o}, \tag{1}$$

where Q_{zo} is the frequency of free vertical oscillations with the mean beam current $I(A) = 0$, ΔQ_z is the shift in free vertical oscillation frequency produced by the beam current, β – relative particle speed, γ – relativistic factor, a – beam radius (cm), $f = f_o q$ – operating frequency (MHz), f_o– – rotation frequency, q – harmonic number, B – bunching factor, m – number of bunches on the orbit, F – the factor regarding beam image on vertical conducting walls of accelerator, R – accelerator radius (cm), r_o – classical particle radius (cm).

When substituting Q_{zo} and ΔQ_z by Q_{ro} and ΔQ_r in formula (1) it is possible to calculate the maximum beam current in the radial direction.

One usually chooses the initial frequency value in the range between the resonance frequency values (integer or half-integer or vice versa) with a permissible frequency shift of about 0.15–0.2. This conclusion was drawn when estimating shortened equations of motion in explicit form disregarding the energy gain per turn.[1,2]

As has been discussed in papers[2,3] in the case of the integer resonance $Q = S$ dynamic crossing the amplitude of vertical particle oscillations is

$$z = \frac{R\epsilon_s}{\sqrt{(Q_z^2 - S^2)^2 + \delta^2 Q_z^2}}, \tag{2}$$

where $\delta = \gamma eV/[\overline{H}\sqrt{\gamma^2 - 1}]$ is the coefficient of friction ("electromagnetic" friction), eV – energy gain per turn (MeV/turn), $\epsilon_s = H_{rs}/\overline{H}$ – relative value of the S^{th} harmonic of the radial magnetic field component H_r, $\overline{H}$ – the mean magnetic field at radius R (cm).

The half-integer resonance is less hazardous compared with the integer one. As a first approximation regardless of the coefficient of friction, the maximum amplitude in the half-integer resonance zone is calculated from the formula[2,3]

$$z \approx 1.2 z_o \frac{\pi H_{rs}}{\overline{H} S} \left(\frac{E_o}{2eV} \right)^{1/2}, \tag{3}$$

where E_o is the particle rest energy. The amplitude excited in the resonance zone will be considerably smaller depending on the coefficient of friction.

In ring accelerators the injection of considerable beam current is possible if the frequency shift is increased from 0.15–0.2 up to 0.6. Let us consider this method of particle injection for use in cyclotrons and synchrotrons with strong focusing.

In ring cyclotrons the orbit radius is continuously increasing during injection. Calculations for the PSI ring cyclotron with proton energy 590 MeV at the injection energy 72 MeV, R=200 cm, $\overline{H} = 5940$ G, $Q_{zo} = 0.95$, $eV = 2.4$ MeV/turn[4] in the case of $Q = 0.5$, $H_{rs} = 0.5$ G show that the value of the incoherent vertical amplitude $z = 0.007\ z_o$ cm, which is insufficient. As formula (1) shows, the frequency shift decreases in a cyclotron when the beam current is conserved and the particle energy increases, through the factor $\beta^2\gamma^3$. Because of this the growing frequency Q will cross the half-integer resonance of 0.5 for the second time, but the amplitude increase will be less compared with the first crossing. The injected beam current is increased by a factor of 2 for a permissible frequency shift of 0.5 instead of 0.25.

During injection the frequency decrease caused by the beam load is partially compensated by the frequency increase for the particles with amplitude different from zero.

Injection into a synchrotron (proton, electron) is quite different due to the fact that at a constant value of magnetic field the particles in the dynamic regime will have a bigger radius after the first turn. This method allows the energy to be decreased by the value of energy gain per turn, leading to a little bit smaller radius. The radius increases after one turn. Then the magnetic field increases over the period in which the particles are accelerated up to the full energy.

So, in the case of a proton synchrotron – the TRIUMF KAON Factory booster project with injection energy 450 MeV ($\beta = 0.737$, $\gamma_0 = 1.48$), $R = 348$ cm, $Q_{zo} = 7.22$, $eV = 0.21$ MeV/turn[5]) calculation from formula (2) with $Q_z = S = 7$, $H_{rs} = 0.5$ G shows the value of the excited vertical amplitude $z = 0.86$ cm. When the energy increases, the frequency also increases and will cross the integer resonance for the second time, but the amplitude increase will be less compared with the first crossing. When the booster is at the full proton energy of 3 GeV, ($\beta = 0.971$, $\gamma = 4.8$) the frequency shift will decrease to 0.01 and the coherent amplitude of forced oscillations will be 0.17 cm. Assuming a frequency shift of 0.6 instead of 0.15 one has a four-fold increase in the injected beam current.

In the case of the IHEP booster proton synchrotron with a proton energy of 1.5 GeV at the injection energy of 30 MeV ($\gamma = 1.03$), $R = 1600$ cm, $\overline{H} = 500$ G, $Q_{zo} = 3.8$, $eV = 0.043$ MeV/turn[6]) calculations from formula (3) with $Q_z = 3.5$ and $H_{rs} = 0.5$ G show the value of the incoherent amplitude $z = 0.77\, z_o$ cm. With a permissible frequency shift of 0.6 instead of 0.2 the beam current can increase by a factor of three at injection.

Figure 1 shows the change of Q_z frequency at injection and as the kinetic energy W of the particles increases in the PSI, TRIUMF and IHEP accelerators.

1. CONCLUSIONS

An injection method for accelerators is suggested and analytically substantiated. The method is as follows. In the dynamic regime the initial frequency of free vertical oscillations placed between integer and half-integer resonances or vice versa, decreases with beam intensity increase during injection, crossing the resonance, but increases with subsequent acceleration, crossing the resonance for a second time and approaching the initial frequency value at the full particle energy in the accelerator. The given maximum increase over the space charge in an accelerator can be used at initial frequency values Q_z and $Q_r > 0.5$. This method allows the beam intensity of operating accelerators to be increased several-fold. The method can be used in storage rings when some acceleration of the particles takes place.

2. REFERENCES

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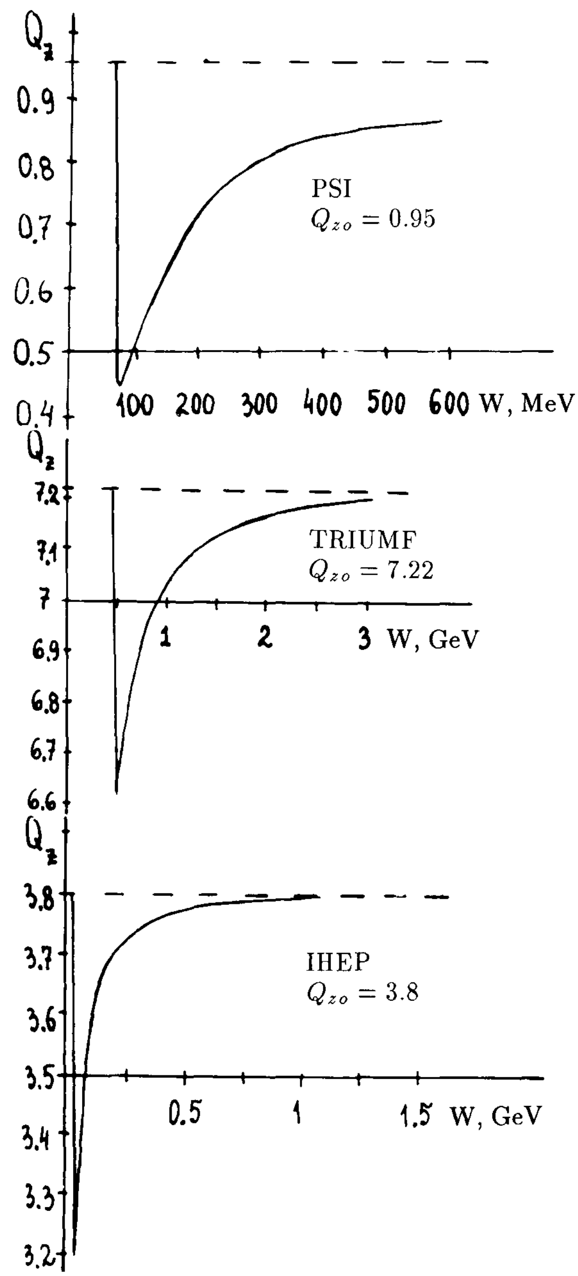

Fig. 1.