THE INDUCTION SYNCHROTRON WITH A CONSTANT MAGNETIC FIELD

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Abstract

In this paper the possibility of accelerating charged particles in a "nearly constant" orbit in a constant magnetic field is discussed.

The trajectories of the accelerated particles are formed by set azimuthally short bending magnets in which the deflection angle is independent of the particle energy.

Focusing of the beam is carried out by the alternating field bending magnets and quadrupole lenses.

The particles are accelerated by the electric field induction sections. Stability of longitudinal oscillations is determined by the shape of the top of the accelerating pulse.

INTRODUCTION

- Features Traditional cyclic accelerators:

1. Accelerators with a constant magnetic field.
   - High ranges of change in orbital radius.
   - Heavy weight of magnets.
2. Accelerators with a constant radius of an equilibrium orbit
   - Magnetic strengths depends on energy of ions.
   - Resonant frequencies of the HF-field depends on energy of particles (cyclic frequency).

- The Induction Synchrotron with Constant Magnetic Field

1. The Magnetic field is constant in time.
   - The Orbital radius $r \sim r_{max}$
   - Particle trajectories – arc chords.
   - $\Delta r = r_{max} - r \leq r_{max}(\pi/N)^2$, N - arc chord number.
2. The Induction accelerating electric field:
   - Isn't present resonant systems with a variable frequency.
   - Synchronization is carried out by sync pulses.

Scheme accelerator with a constant magnetic field is shown in Fig. 1.

MAGNETIC SYSTEM OF THE SYNCHROTRON

1. Special sections of magnetic dipoles form the near-circular orbit with $r \simeq r_{max}$ radius.

- Each dipole of section (Fig.2) deflects the accelerated beam on $\Delta\Theta/2$ angle.
- This angle doesn't depend on energy of particles if the internal border of dipoles corresponds to equality

$$x = \pm\left[(r_{max} - r)\sin\frac{\Delta\Theta}{2} + x_0\right]$$

x - distance of internal border of dipoles to bisector of angle $\Delta\Theta$

x_0 - the size determined by a concrete design of section

r , r_{max} -the current and maximum radiuses determined by energy of a particle.

2. The focusing forces of magnetic section.

- Magnetic fields of section focus the accelerated particles in the horizontal plane.
- Magnetic forces of section defocus the accelerated particles in the vertical plane.
- Additional lenses on an entrance and an exit of magnetic section are required.

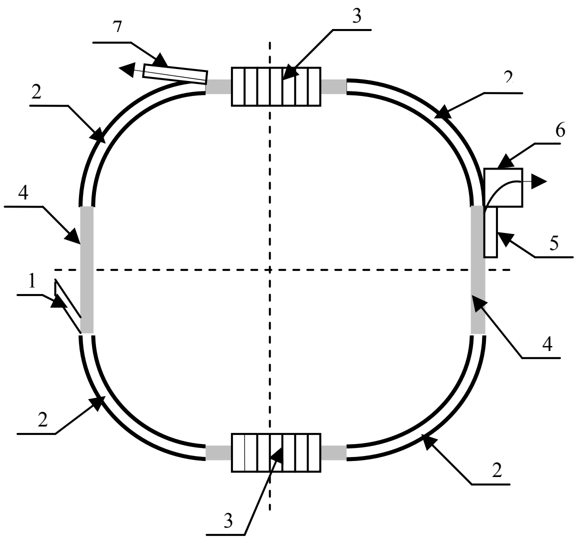

Figure 1: Scheme accelerator with a constant magnetic field. 1 - Injector; 2 - Set of special sections of magnetic dipoles; 3 - Induction accelerating sections; 4 - Straight-line segments; 5-7 - System of fast and slow beam extraction.

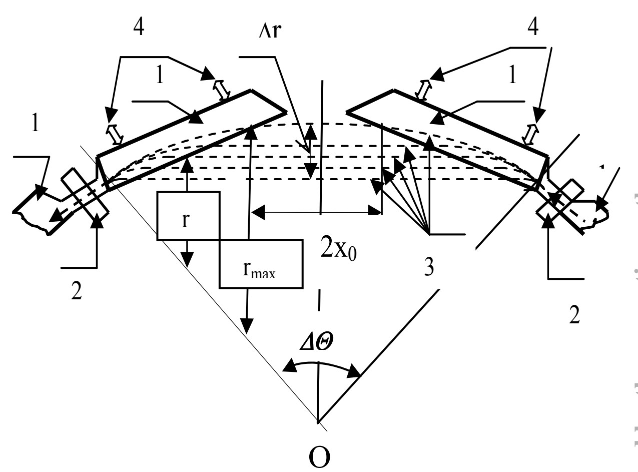

Figure 2: The warrant of the bending magnetic section using dipoles with a uniform field. 1 - Dipoles with a uniform field; 2 – Additional focusing lenses; 3 – Beam trajectories; 4 - System tuning the beam trafctores, 5 – ΔΘ - The center angle of a beam deflection.

ISBN 978-3-95450-170-0

DYNAMICS OF PARTICLES IN MAGNETIC SECTION

Vertical Plane of Section

- Matrix of magnetic section

$$[M_z]=[f_1][m_z][f_z][x][f_z][m_z][f_1]$$

$$[f_1]=\begin{bmatrix}1 & 0\\ -1/f_{1z} & 1\end{bmatrix}$$ – Matrix of additional lenses

$$[m_z]=\begin{bmatrix}1 & m\\ o & 1\end{bmatrix}$$ – Matrix of magnetic dipoles $m = r\Delta\Theta/2$

$$[f_z]=\begin{bmatrix}1 & 0\\ 1/f & 1\end{bmatrix}$$ – Matrix of a fringing field of dipoles $f = rtg\Delta\Theta/4$, [3]

$$[x]=\begin{bmatrix}1 & 2x\\ 0 & 1\end{bmatrix}$$ – Matrix of drift of particles between dipoles

$$x=\left[(r_{\max}-r)\sin\frac{\Delta\Theta}{2}+x_0\right]$$

Horizontal Plane of Section

- Matrix of magnetic section

$$[M_r]=[f_2][m_r][f_r][x][f_r][m_r][f_2]$$

$$[f_2]=\begin{bmatrix}1 & 0\\ -1/f_{2r} & 1\end{bmatrix}$$ – Matrix of additional lenses

$$[m_r]=\begin{bmatrix}\cos\Delta\Theta/2 & r\sin\Delta\Theta/2\\ -\frac{1}{r}\sin\Delta\Theta/2 & \cos\Delta\Theta/2\end{bmatrix}$$ – Matrix of magnetic dipoles

$$[f_r]=\begin{bmatrix}1 & 0\\ -1/f & 1\end{bmatrix}$$ – Matrix of a fringing field of dipoles $f = rtg\,\Delta\Theta/4$

Of special interest is the case where the focal lengths for additional input and output bending magnetic section are:

$$f_{1z}=(f+m) \quad \text{- for } z\text{-plane} \qquad (1)$$

$$f_{2r}=f \quad \text{- for } r\text{–plane} \qquad (2)$$

In this case, the matrices M_z and M_r are equivalent drift matrices:

$$[M_z]=\begin{bmatrix}1 & L_z\\ 0 & 1\end{bmatrix}$$

$$L_z=2(1+m_z/f)[m_z+x(1+m_z/f)]$$

$$[M_r]=\begin{bmatrix}1 & L_r\\ 0 & 1\end{bmatrix}$$

$$L_r=2\left[x-f\left(1+\cos\Delta\Theta/2\right)\right]$$

Using on an entrance and an exit of bending sections a combination of a symmetric lens with focal length

$$f_S=2f\frac{(m_z+f)}{m_z+2f}$$

and a quadrupole lens with focal length

$$f_q=\pm 2f\frac{(m_z+f)}{m}$$

we will receive the demanded parameters of a combination of lenses

$$\frac{1}{f_S}-\frac{1}{|f_q|}=\frac{1}{f_1} \qquad \frac{1}{f_S}+\frac{1}{|f_q|}=\frac{1}{f_2}$$

and the simultaneous fulfillment of condition (1) and (2).

5. At small angles of $\Delta\Theta$, when $tg\frac{\Delta\Theta}{4}\cong\frac{\Delta\Theta}{4}$

$$f_S=\frac{3}{8}r\Delta\Theta \qquad f_q=\pm\frac{3}{4}r\Delta\Theta$$

FOCUSING OF A BEAM AT ACCELERATION OF PARTICLES

- The ***FODO*** mode of focusing can be used at acceleration of particles. A focusing period matrix for the case where the conditions (1) and (2) are satisfied

$$[N_{z,r}]=\begin{bmatrix}1 & L_{z,r}\\ 0 & 1\end{bmatrix}\cdot\begin{bmatrix}1 & 0\\ 1/f_{z,r} & 0\end{bmatrix}\cdot\begin{bmatrix}1 & L_{z,r}\\ 0 & 1\end{bmatrix}\cdot\begin{bmatrix}1 & 0\\ -1/f_{z,r} & 1\end{bmatrix}=\begin{bmatrix}N_{11}^{z,r} & N_{12}^{z,r}\\ N_{21}^{z,r} & N_{22}^{z,r}\end{bmatrix}$$

$$N_{11}^{z,r}=1-\left(L_{z,r}/f_{z,r}\right)^2-L_{z,r}/f_{z,r}$$

$$N_{12}^{z,r}=\left(2+L_{z,r}/f_{z,r}\right)\cdot L_{z,r}$$

$$N_{21}^{z,r}=-L_{z,r}/f_{z,r}^2$$

$$N_{22}^{z,r}=1+L_{z,r}/f_{z,r}$$

- Change of a phase of betatron fluctuations for one period of the focusing system is defined by a ratio

$$\cos\sigma_{z,r}=\frac{1}{2}\left(N_{11}^{z,r}+N_{22}^{z,r}\right)=1-\frac{1}{2}\left(\frac{L_{z,r}}{f_{z,r}}\right)^2$$

or

$$\sin\frac{\sigma_{z,r}}{2}=\frac{1}{2}\frac{L_{z,r}}{f_{z,r}}$$

CONCLUSION

- Frequencies of betatron oscillations

At $f_r \approx f_z = 4.5[r_{max}\Delta\Theta + 2x_0]$

$$2\Delta\Theta = 30^0;\ r_{max}\Delta\Theta >> 2x_0$$

frequency range of betatron oscillations during acceleration is shown in Table 1

Tab.1 frequency range of betatron oscillations during acceleration

$\nu_{z,r}$	$P << P_{max}$ $r << r_{max}$	$P = 0,5P_{max}$ $r = 0.5r_{max}$	$P = P_{max}$ $r = r_{max}$
ν_z	6	9.2	10.7
ν_r	11.6	12	12.8

- For 200MeV proton accelerator, B = 1T (NdFeB-magnet), r_{max} = 2.15m, $\Delta r = r_{max} - r_{min}$ = 2.2cm
- At beam emittance $\varepsilon = 30\pi mm.mrad$ equibrium radius, about which varies the beam envelopes are:

$$a_{z,r} = \sqrt{\varepsilon r_{max}/\nu_{z,r}} = 2.2 - 3.3mm$$

- The duration of the accelerating pulses of induction system [4]:

$$\tau_{ind} \leq 0.5\tau_c = \pi r_{max}/v_{max} = 40ns$$

- Azimuthal stability is provided with an inclination of a table of the accelerating induction impulses (See Fig.3)

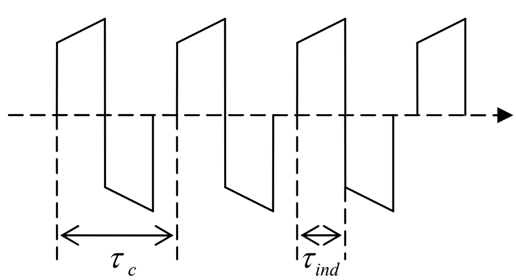

Figure 3: The accelerating induction pulses
τ_c – the acceleration cycle duration,
τ_{ind} – the induction pulse duration.

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ISBN 978-3-95450-170-0