THE MODIFIED BETATRON PROTOTYPE DEDICATED TO ELECTRON COOLING

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Abstract

The use of an electron cooling system with a circulating electron beam permits to avoid the problems of a traditional electron cooling system and cool down the heavy particles in a few GeV energy range. Particularly, such a system can be applied to the antiproton Recycler at Fermilab (antiproton energy 8 GeV). In this case the Recycler ring is to be equipped with an additional electron one, which is periodically filled up with new portion of cold electrons. The electron beam circulates in longitudinal (quasitoroidal) magnetic field, and the long term stability of the beam is provided with additional spiral coils, which form a quadrupole magnetic field. In the straight section, where the electrons cool the antiprotons this quadrupole field is absent. The acceleration of the electron beam without the distortions caused by RF system of linear accelerators is achieved by using of induction acceleration. Such a ring is similar to the modified betatron and its modification called “stellatron”.

The main limitations of the electron cooling system based on the modified betatron are discussed. The general parameters of the modified betatron prototype designed at the JINR in order to test the medium energy electron cooling system are presented.

1 INTRODUCTION

The electron cooling system with circulating electron beam based on the modified betatron was proposed in [1,2] as a possible way to avoid the problems of a traditional cooling system at medium electron energy. Main peculiarities of this system are the following: the use of the longitudinal magnetic field for an intense electron beam focusing and spiral quadrupole coils to provide the long term stability of the drift motion of the electron beam, induction acceleration of the electrons. In order to test such a system, its prototype called Modified Betatron Prototype (MOBY) was designed at the JINR. The main goal of the MOBY creation is to study the particle motion dynamics, including electron injection and extraction, induction acceleration of the beam and its stability.

2 GENERAL DISCRIPTION

The Modified Betatron Prototype (Fig. 1) is an electron induction accelerator at maximum electron energy of 4.36 MeV with longitudinal magnetic field and additional quadrupole spiral focusing field. The electron acceleration is provided by the betatron inductor, which is supplied by the current pulses of the duration of 20 msec. The repetition frequency of the inductor current pulses is about 1 Hz, and the electron beam circulates in the ring after acceleration up to 1 sec.

The general parameters of the MOBY (Table 1) were chosen close to requirements of the electron cooling system at the Fermilab Recycler [3].

Table 1.

General parameters of the Modified Betatron Prototype.

Ring parameters		
Circumference, m	18.28	
Longitudinal magnetic field, G	1000	
Major radius of the toroids, m	1.45	
Bending magnetic field, G	1.75 – 124	
Gradient of the quadrupole magnetic field, G/cm	1 – 2	
Electron beam radius, cm	1.5	
Residual gas pressure, Torr	10^{-10}	
Electron beam parameters		
	At injection	After acceleration
Energy, keV	10	4360
Current, A	0.1	0.5
Revolution period, nsec	300	60
Acceleration cycle		
Induction voltage amplitude, V	50	
Repetition frequency, Hz	1	
Cycle duration, msec	10	

The circumference of the Recycler cooling system has to be longer of the MOBY circumference - about 120 m. MOBY can be upgraded to full-scale electron cooling system in the electron energy range of a few MeV by addition of several sections of straight solenoids, which are of the length of about 1 m.

The lower limit of the focusing longitudinal magnetic field in the electron ring is determined by two conditions: the electron drift velocity (in the crossed fields of the electron beam and the solenoid) is to be smaller than the electron thermovelocity and Larmor radius of the electron transverse motion is to be smaller of the distance between electrons - so called condition of the electron magnetisation [4].

For Recycler cooling system, where the electron temperature is to be of T_e ~ 0.2 eV, these conditions are very modest: at electron current of 2 A the magnetic field value has to be higher than 200 G. However, to prevent a heating of the electron beam by the field distortions at junctions of solenoids of different geometry (straight and toroidal) so-called adiabatic condition is to be satisfied: $2\pi\rho << L$, where $2\pi\rho$ is the step of the electron Larmor spiral, L is characteristic length of the distortion, which is approximately equal to the solenoid diameter. From this point of view the magnetic field value of several kG is preferable.

The period of the electron circulation is restricted by the process of the thermorelaxation between the "hot" ion (antiproton) beam and "cold" electron one, and for the Recycler parameters is about 1 sec [1].

Vacuum conditions in the electron ring are determined by electron beam heating in multiscattering on residual gas. At the electron beam angular spread of 10^{-4}, multiscuttering characteristic time is of order of several tens of msec at residual gas pressure P=10^{-10} Torr. This value is long enough for testing of the acceleration process, but the residual gas pressure has to be less than 10^{-10} Torr to keep the electron beam quality during cooling process.

2 WORKING CYCLE

Bending field in the toroids is produced by two kinds of coils – the first ones operate in the continuos mode operation, the second ones – in the pulsed mode one. The permanent bending field corresponds to the maximum electron energy. The alternative magnetic field has direction opposite to the permanent one. The coils of the alternative bending field and the coils of the inductor are fed with the same power supply which operats in the pulsed mode.

Working cycle of the Modified Betatron Prototype includes the following steps:

1.Current pulse excites the magnetic field of the inductor and bending field coils. On the front slope of this pulse the voltage at the acceleration gap is negative (decelerating), the sum value of the bending field in toroids decreases to zero.

2. On the back slope of the inductor current pulse the voltage on the acceleration gap changes sign and the bending field in the toroids increases. When the bending magnetic field corresponds to the electron injection energy, the positive voltage pulse, applied to the grid electrode of the electron gun, starts the electron beam generation. The electron beam is injected into betatron by the drift in the field of special kicker coil.

3. When the ring is filled with electrons, the kicker is switched off.

4. The electron beam acceleration is provided during the back slope of the inductor current pulse.

5. Between two pulses of the inductor current the accelerated beam circulates in the ring at a constant energy.

6. On the front slope of the next pulse of the inductor current electron beam is decelerated. After that, the kicker pulse displaces the beam to the collector (beam dump).

4 ELECTRON ACCELERATION AND ELECTRON BEAM QUALITY

The acceleration voltage generated by inductor is to be applied to a gap in vacuum chamber (ceramic insulator). Bending magnetic field in the toroids has to correspond to electron momentum during acceleration cycle. Alternative magnetic flux through the electron orbit produced by bending coils generates additional electric field, which also influences on the particle longitudinal motion.

Taking into account all these effects one can write the equations for electron momentum p(t) and orbit variation during acceleration:

$$\frac{dp}{dt} = e\bar{E}(t), \; \bar{E}(t) = \frac{\sum V(t)}{C},$$

$$V(t) = -\frac{1}{c}\frac{\partial \Phi}{\partial t}, \; R(t) = \frac{p(t)c}{eB(t)}, \qquad (1)$$

where $\bar{E}(t)$ is the averaged over the orbit acceleration electric field, ΣV is the sum of inductor and bending coils voltage, C is the ring circumference, Φ is the magnetic flux through the particle orbit produced by inductor and bending coils, *R* - the major toroid radius, *B(t)* - the bending magnetic field in the toroids. Requiring *R(t)=R=const* one has:

$$\frac{\partial B}{\partial t} = \frac{c}{eR}\frac{dp}{dt}. \qquad (2)$$

Combining (1) and (2) one obtain

$\frac{\partial B}{\partial t} = \frac{c}{RC}\sum V$, that give us

$$B(t) = B_{inj} + \frac{c}{RC}\int_0^t \sum V(\tau)d\tau =$$

$$B_{inj} - \frac{1}{RC}\left(\Phi(t) - \Phi(0)\right), \qquad (3)$$

where $B_{inj} = \frac{p_{inj}c}{eR}$ is the value of the bending magnetic field at injection.

For instance, if the particle orbit is chosen so that bending field flux is equal to zero and the inductor flux varies in time as $\Phi_{ind} = \Phi_{max} \sin \omega t$, then the bending field, according to the equation (3), has to have the following dependence on time:

$$B(t) = B_0 + \frac{\Phi_m \sin \omega t}{RC}. \qquad (4)$$

This requirement is satisfied, when the bending coils and inductor are fed with the same power supply.

The electron kinetic energy $\varepsilon(t)$ increases in time at acceleration in accordance with the following:

$$\varepsilon(t) = \sum_{n=o}^{n(t)} \varepsilon_n \, ,$$

$$n(t) = \left[\frac{t}{T_{rev}(t)}\right], \quad \begin{cases} \varepsilon_{n+1} = \varepsilon_n + V\cos\varphi_n \\ \varphi_{n+1} = \varphi_n + \omega T_{rev}(t) \end{cases}, \qquad (5)$$

where $T_{rev}(t) = C/v(t)$ is the revolution period, ω is the frequency of magnetic fields variation (see (4)), φ is the acceleration voltage phase at when electron crosses the acceleration gap.

The numerical solution of the equation (5) gives us the acceleration voltage amplitude for chosen final kinetic energy. Injection phase is determined by bending magnetic field that corresponds to initial energy. So, for $\omega=2\pi\cdot 50$ Hz, and ε_{fin} = 4.36 MeV the acceleration voltage amplitude is about 50 V.

The energy spread of the accelerated electron beam is caused particularly by variation of the acceleration voltage during revolution period, it is equal to:

$$\Delta\varepsilon = e\left(\frac{\partial V}{\partial t} T_{rev}\right)_{inj} - e\left(\frac{\partial V}{\partial t} T_{rev}\right)_{eject}\ , \qquad (6)$$

here V is the accelerating voltage. When $V=V_0 sin(\omega t)$ and initial and final phases of electron acceleration are symmetrically placed around the voltage maximum, the relative energy spread of electrons after acceleration can be estimated by the following formulae:

$$\frac{\Delta\varepsilon}{\varepsilon} \approx \left(\frac{C\omega}{c}\right)^2 \frac{1-\beta_{inj}}{\beta_{inj}\overline{\beta}}\ . \qquad (7)$$

Here β_{inj}, $\overline{\beta}$ are electron velocities in c units at injection and averaged over acceleration period. These estimations show that for the acceleration frequency of the order of 50 Hz the acceleration process does not limit the electron momentum spread value. Therefore, the electron beam momentum spread after acceleration is determined by effects of the beam space charge. Particularly, the threshold of the microwave coherent instability is of the order of several hundred mA when momentum spread is about $1 \cdot 10^{-4}$ [5]. The angular spread of the circulating electron beam is determined by the stability of the transverse particle motion during acceleration. The radius of the particle Larmor rotation in the longitudinal magnetic field increases with particle energy and at fixed value of the focusing gradient the working point crosses the resonance “islands”. This problem can be avoided by using a “fast” electrostatic spiral quadrupole focusing electrodes, which are placed inside the vacuum chamber. In this case the gradient of the focusing field can be operated during acceleration to avoid the resonance conditions. When the particle motion is stable, the angular spread is determined mainly by the value of quadrupole gradient and errors of the bending magnetic field, and its value is of the order of magnitude of 1 mrad [5].

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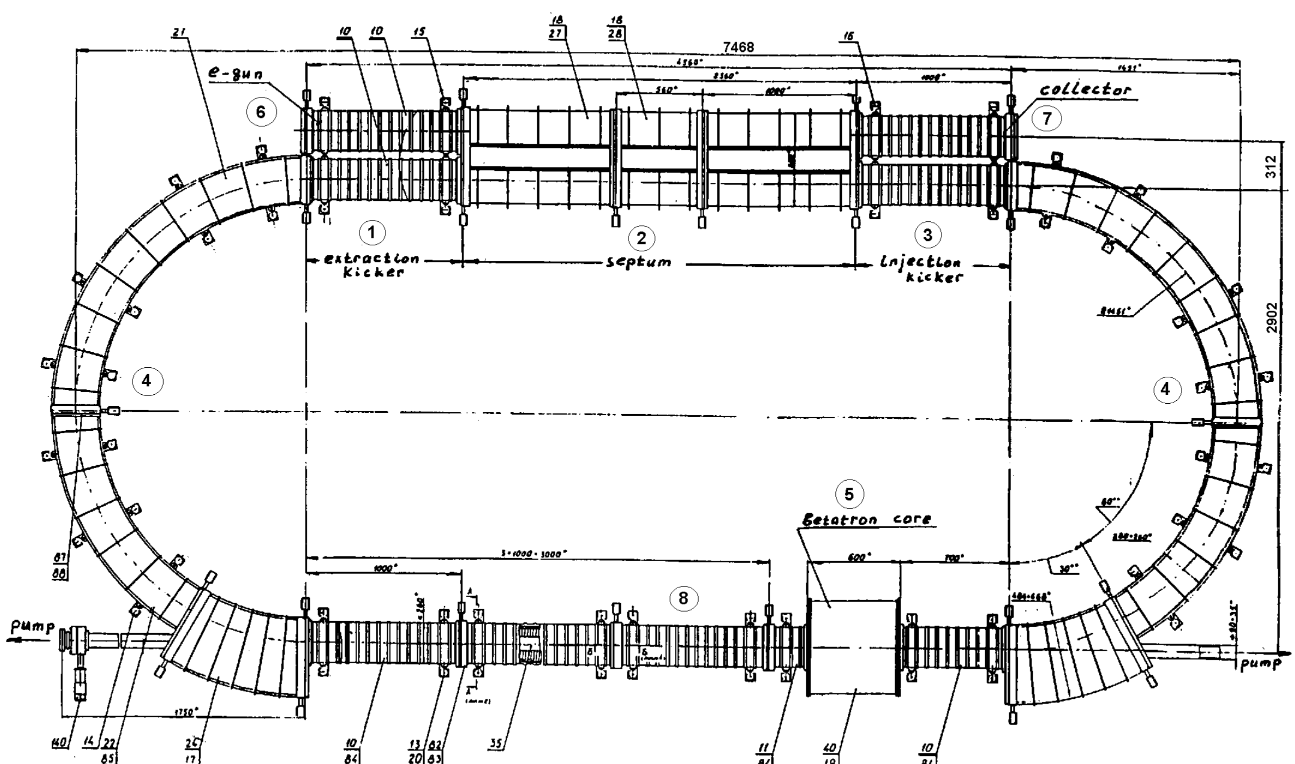

Fig 1. The assembly drawing of the Modified Betatron Prototype: 1. extraction kicker, 2. septum, 3. injection kicker, 4. toroidal sections, 5. betatron core, 6. electron gun, 7. electron collector, 8. cooling section.