FFAG(Fixed-field Alternating Gradient) Proton Synchrotron

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Abstract

Fixed field alternating gradient(FFAG) focusing is attractive for acceleration of high intensity hadron beams because acceleration cycle could be increased. The magnetic field of FFAG is static, therefore, the repetition rate of acceleration could be increased more than 10 times larger than that of ordinary rapid cycling synchrotron(RCS) if an efficient high voltage RF accelerating system becomes available. Recently, a new type of high gradient RF cavity (HGC) using high permeability magnetic alloy (MA) has been developed and FFAG synchrotron becomes very promising. In order to clarify the feasibility of rapid cycling FFAG synchrotron experimentally, proof-of-principle (POP) machine, which accelerates protons up to 1MeV with 1kHz repetition, is under development. We have also made several designs on high intensity proton accelerators with FFAG synchrotron for various applications such as spallation neutron source, proton driver for muon collider and accelerator driven system(ADS) for energy breeder.

1 Introduction

High intensity medium energy (1GeV~ 10GeV) proton beams are required for many applications such as spallation neutron source, proton-driver for muon collider, accelerator-driven system (ADS) for nuclear energy production, etc. In these applications, large beam power of more than 1MW is requested. In order to realize such large beam power with ordinary proton synchrotron, rapid cycling of beam acceleration is inevitably. For example, an high intensity cyclotron with superconducting magnets has been discussed for ADS as a possible candidate for the cyclic accelerators. This is believed mostly because of the experience at the PSI cyclotron, which has obtained about more than 1MW beams so far. As for a synchrotron, it has been thought that it would be almost useless for ADS because the operation is a pulsed mode and the average beam current is small. The magnetic field is time varying according to beam acceleration in the synchrotron, the eddy-current power loss in the magnets becomes serious when the repetition rate of the accelerating cycle is increased and the magnetic field ramping exceeds more than 200T/sec. On the other hand, the accelerated particle number per pulse is limited by the space-charge effect. Practically, the maximum repetition of the rapid cycling synchrotron is limited to be less than 50Hz or so. Therefore, the maximum available beam power would be at most about 1MW[1]. However, the beam in the synchrotron is stable, because it is strongly focused in the transverse and longitudinal directions, and the instantaneous beam current in the ring becomes very large. Fixed-field alternating gradient (FFAG) synchrotron, thus, becomes attractive for this purpose.

Another issue is an electric power efficiency in operation of high intensity accelerator. For such large beam power accelerator, the electric power required for operation increases to an acceptable level if the electric power efficiency is small. The operational electric power efficiency of the accelerator is defined by the ratio of the total beam power to the total electric power requested for operation of the whole accelerator system. The accelerator comprises mainly the magnet and the rf accelerating systems. During operation, the 80-90% of the total electricity of the accelerator is dissipated for these two systems. The electric power consumed by the magnet system can be dramatically reduced by using a superconducting technique, and can become negligibly small. On the other hand, the electric power dissipated by the rf accelerating system would still be an issue even if a superconducting rf system is applied. A superconducting rf cavity system is inevitably essential in a linear accelerator system to reduce the total rf power requested for operation by increasing the effective shunt impedance. On the other hand, for a cyclic accelerator, such as cyclotron or synchrotron, the situation is more reluctant, because the cyclic accelerator is regarded as being a very long accelerator. More than 50% electric power efficiency seems to be possible in a cyclic accelerator, even if the normal conducting rf cavity is used. In case of the ordinary synchrotron, the eddy current loss becomes huge if the repetition rate increases more than 10Hz, therefore, the power efficiency can be very bad for the ordinary synchrotron. Since a superconducting maget could be used for the FFAG synchrotron because the magnetic field is static, the power efficiency becomes pretty good .

2 FFAG focuding synchrotron

A fixed-field alternating gradinet(FFAG) synchrotron seems to be very attractive for this purpose, because the repetition rate of the accelerating cycle could be raised ten times or more compared to that of the ordinary synchrotron. The idea of a FFAG synchrotron was proposed independently by Ohkawa[2], Symon[3] and Kolomensky[4] in the early 1950's, and electron-beam machines demonstrating this principle have been successfully built in the MURA project.[3] In FFAG synchrotron, where the magnetic field is constant in time, the shape of the magnetic field should be such that the betatron tunes for both the horizontal and vertical planes should be constant for all closed orbit, and departing from all of the dangerous resonance lines. The condition above is called " zero-chromaticity".

$$\frac{\partial}{\partial p}\left(\frac{K}{K_0}\right)\Bigg|_{\vartheta=const.}=0, \quad \frac{\partial n}{\partial p}\Bigg|_{\vartheta=const.}=0.$$

A magnetic field satisfying the scaling conditions described above must generally have the form ,

$$B(r,\theta)=B_i\left(\frac{r_i}{r}\right)^n F\left(\theta-\varsigma\ln\frac{r}{r_i}\right),$$

where ς is a spiral angle. If ς is zero, the magnetic field does not depend on θ, and the corresponding orbit points are distributed on a radial vector. The type of having this magnetic shape is called " radial sector". One the other hand, if θ behaves in a logarithmic manner, such as

$$\theta-\varsigma\ln\frac{r}{r_i}=\text{const.},$$

the orbits remain geometrically similar, but move around the beam center towards larger radii. This type is called " spiral sector".

The FFAG synchrotron is very attractive for acceleration intense proton beams as described above and several proposals have been submited.[5][6] However, no practical proton-beam machine has been built so far. One of the most difficult technical issues to realize a high-repetition FFAG synchrotron is rf acceleration. The requested accelerating rf voltage per one turn is

$$\Delta V=2\pi(1+n)\left(\frac{dr}{dt}\right)p.$$

Here, dr/dt is the orbit excursion rate. In the case of a1GeV FFAG synchrotron with the repetition rate of 1kHz, the requested rf voltage becomes almost 1MV. This is a rather difficult number if an ordinary ferrite-loaded rf cavity is applied, which has been conventionally used for the proton synchrotron so far. In the ordinary ferrite-loaded rf cavity, the maximum accelerating field gradient is at most 10 kV/m or so. Therefore, more than 100m long straight sections are necessary for the rf cavities in the ring, although the total circumference of the 1GeV FFAG synchrotron would be less than 150m. Recently, a new type of high-gradient rf cavity using a high-permeability magnetic alloy has been developed at KEK for the JHF project, and a field gradient of 100kV/m has been successfully achieved. [7] Using this high-gradient cavity, the most difficult technical issue in realizing a high-repetition FFAG synchrotron can be solved.

A preliminary design of the 1.5GeV and 10MW beam power FFAG synchrotron has been carried out.[8] The fundamental parameters are listed in Table 1.

Table.1 Fundamental parameters of 1.5GeV FFAG synchrotron.

Injection Energy	0.25 GeV
Extraction Energy	1.5 GeV
Beam Intensity	$5.5\text{x}10^{13}$ppp
Repetition Rate	750Hz
Average Beam Current	6.6mA
No. of Sectors	16
Circumference Factor	2.68
Average Beam Radius	
injection	12.2m
extraction	13.4m
Magnetic Field	
injection	0.536T
extraction	1.5T
Field Index	10.5
Effective Field Index	3.9
Spiral Angle	64.6 deg
Fractional Angle	8.34 deg
Betatron oscillation tune	
horizontal	3.73
vertical	3.23
Transition Gamma	3.442
Max. RF Voltage	0.56MV
RF Frequency	2.39MHz~3.3 MHz

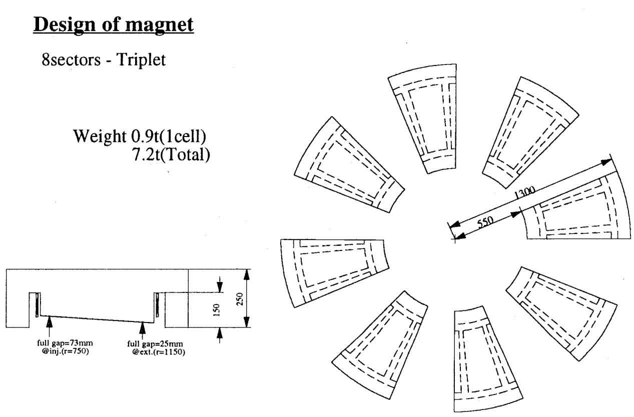

Fig.1 1MeV MOS proof-of-principle machie.

3 POP(Proof-of-principle) machine of 1-MeV and 1-kHz FFAG synchrotron

In order to clarify the availability of very rapid cycling in FFAG synchrotron, we have been developing a small POP(proof-of-principle) machine. In this POP machine, the maximum energy is limited to 1MeV but the repetition rate of acceleration is 1kHz. The magnet configuration is a radial sector type and eight fold symmetry is chosen as shown in Fig.1. Each sector consists of three dipole magnets which form a triplet focusing configuration DFD(defocus-focus-defocus) and field index of each dipole magnet is 2.5, respectively. The maximum magnetic fields of the focusing and defocusing dipole magnets are 0.5T and 0.2 T, respectively. The magnetic field configurations in three dimensional directions are calculated with OPERA-

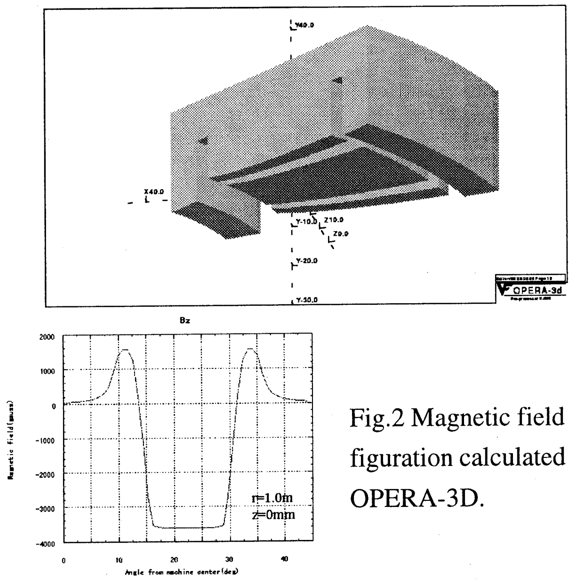

Fig.2 Magnetic field configuration calculated with OPERA-3D.

3D (Fig. 2) and their results are used for beam tracking simulation. The average beam radius changes from 0.81m to 1.13m according to the increase of beam energy from 100keV to 1.1MeV. The half gap heights of the magnet at the radius of 0.75m and 1.15m are 73mm and 25 mm, respectively.

The betatron tunes for horizontal and vertical directions are varied with field index and the product of the magnetic field and the effective magnet length (Bl-product). The lines in Fig. 3 show the variations of the betatron tunes for both directions calculated with the SAD code. The design values of betatron tunes for horizontal and vertical directions are 2.25 and 1.35, respectively. The open squares and circles in Fig. 3 show the betatron tunes for two different field indices of 2.5 and 2.0, respectively, which are obtained with beam tracking simulation for 3D magnetic field configurations presented in Fig. 2. The betatron tunes are slightly different from those estimated by SAD and change gradually during acceleration. The beam behaviors in the transverse direction obtained by beam tracking simulation are shown in Fig. 4. The rf frequency changes from 0.85MHz to 2.05MHz. At the condition of the constant radial displacement as a function of time (dr/dt=const.), the rf voltage has to be increased from 1.1kV to 3.1kV. This rf voltage can be easily obtained by a magnetic alloy(MA) loaded rf cavity.[7] The longitudinal beam motions calculated by beam tracking simulation are shown in Fig.5.

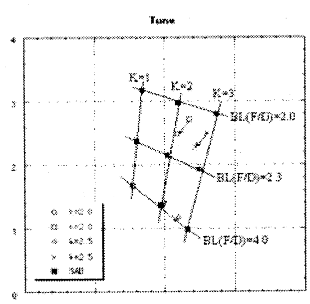

Fig. 3 Betarton tune diagra of 1MeV POP machine..

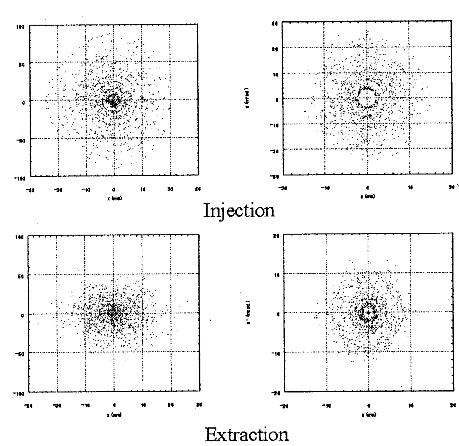

Fig. 4 Particle tracking simulation in transeverse direction.

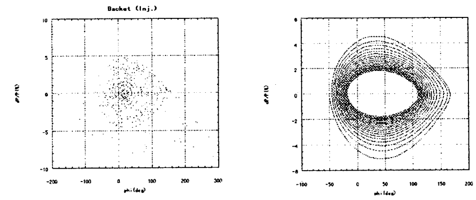

Fig.5 Particle tracking simulation in longitudinal direction.

4 Conclusion

A 1.5GeV and 10MW fixed field alternating gradient (FFAG) focusing synchrotron has been designed. Although the repetition rate for accelerating cycle is rather high, 750 Hz, the required rf voltage is relatively small, only 580, because of its small ring size. A 1MeV POP(proof-of-principle) proton machine with 1kHz repetition is under development.

REFERENCES

[1] JHF Accelerator Design Study Report, KEK Report 97-16.
[2] T.Ohkawa; Proc. of annual meeting of JPS (1953).
[3] K.R.Symon et al.;Phys. Rev. 103 (1956) 1837.
[4] A.A.Kolomensky et al.;ZhETF 33,298(1957).
[5] R.L.Kustom et al.;IEEE,NS-32,2672(1985).
[6] H.Sasaki;GEMINI Design Report, KEK-Report (1985).
[7] Y. Mori, Proc. of EPAC98, Stockholm, 1998, page 299.
[8] Y.Mori, Proc. of Thorium Fuel Cycle, *Genshikaku Kenkyu*, 43(1999)27.