HYBRID ACCELERATOR USING AN FFAG INJECTION SCHEME

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Abstract

A hybrid accelerator using an FFAG injection scheme is proposed for industrial applications. The bending field is constant at an injection time as an FFAG accelerator, and the bending field changes after the injection time as a synchrotron. Both rf accelerator and induction accelerator are practicable. We have designed a very compact 1 MeV electron induction accelerator. Peak current and the repetition are 8 A and 1 kHz, respectively. Beam simulation results show that large beam size at injection time is gradually reduced to small size during acceleration. Proto-type five-sectors spiral bending magnet has been designed and constructed. Outer diameter of the magnet is as small as 100 mm, and the weight is about 3 kg. Magnetic measured results show that rapid cycle repetition can be practicable.

INTRODUCTION

Compact and low price accelerators are necessary for industrial and medical applications. Circular accelerators are generally thought to be smaller and more economy than linear accelerators, when high-energy charged particles are accelerated. But high intensity charged particles cannot be accelerated with conventional circular accelerators, because space charge effects are severe.

A hybrid acceleration scheme has been proposed [1]. The bending field is constant at an injection time as an FFAG accelerator, and the bending field changes after the injection time as a synchrotron. Acceleration with large beam sizes can be done with the scheme, and high intensity beam can be accelerated. This paper describes the hybrid acceleration scheme, an example design result of the hybrid accelerator: 1 MeV electron induction accelerator, and manufactured results of the five-sectors spiral bending magnet.

HYBRID ACCELERATION SCHEME

A hybrid accelerator is combination between an FFAG accelerator and a synchrotron. An FFAG accelerator is a machine with a constant magnetic field and closed orbit radius becomes large in time as the energy of particles increases. A synchrotron is a machine with particles moving on a closed constant circular trajectory where the magnetic field changes in time as the energy of particles increases. A hybrid accelerator is the machine that the magnetic field is constant at an injection time, and the magnetic field changes after the injection time. Both magnetic fields and closed orbits are changed.

$$P = eBR$$

$$\frac{dP}{dt} = eB\frac{dR}{dt} + eR\frac{dB}{dt} \qquad (1)$$

The advantage of the hybrid accelerator is that it can accelerate high intensity beam till high energy. The hybrid accelerator is suitable for an electron accelerator when high repetition rate of the magnetic field can be done. The accelerator is also suitable for an injector of a synchrotron. Both rf accelerator and induction accelerator are practicable. Figure 1 shows an example of the acceleration scenario of the hybrid accelerator with an induction acceleration scheme.

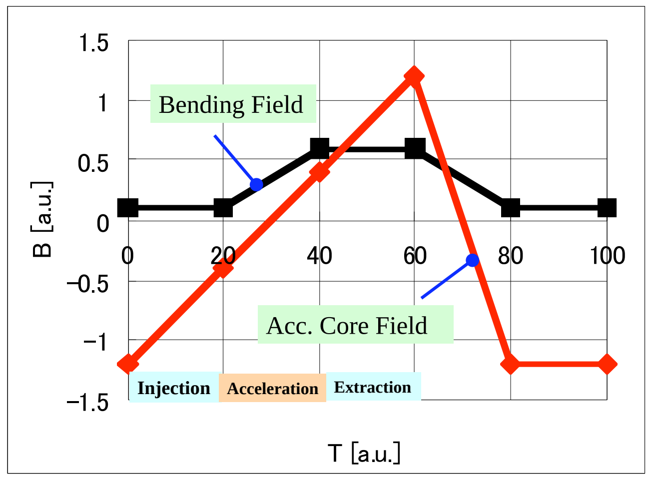

Figure 1: Acceleration scenario of the hybrid accelerator with an induction acceleration scheme.

ELECTRON INDUCTION ACCELERATOR

A compact electron induction circular accelerator (laptop accelerator) is designed with the hybrid acceleration scheme.

Table 1: Basic parameters of an 1MeV laptop accelerator

Maximum Energy	1 MeV
Injection Energy	60 keV
Particle	electron
Magnet type	Spiral sector
K value	0.8
Radii of closed orbit injection/extraction	23mm/28.3mm
Packing factor	0.3
Spiral angle	35 degree
Number of sectors	5
Full outside diameter	100 mm
Betatron tunes horizontal/vertical	1.85/0.8
Repetition rate	1 kHz

As in conventional FFAG designs the magnet is such as to provide a field whose average value varies with radius as r^k, and use of logarithmically spiralled poles permitted possible orbits of particles with different energies to be geometrically similar. Table 1 shows basic parameters of the 1MeV laptop accelerator. It is a 5 sectors 1MeV electron accelerator with the full outside diameter 100 mm. The inner radius of the magnet is determined by the need to accommodate the betatron core. The magnet gap decreases in proportion to the radius and the magnetic field as r^k. The beam extraction radius is 28.3 mm. Figure 2 shows magnetic pole shape of the spiral magnet, and injection and extraction closed orbits. The magnetic fields of an average bending magnetic field (B_{orbit}) and an induction acceleration field (B_{acc}) are as following equations, where B_c, B_0, r_i, and k are field strength of the induction core, average bending magnetic field at the r_0, interior radius of the pole tip, and field index, respectively.

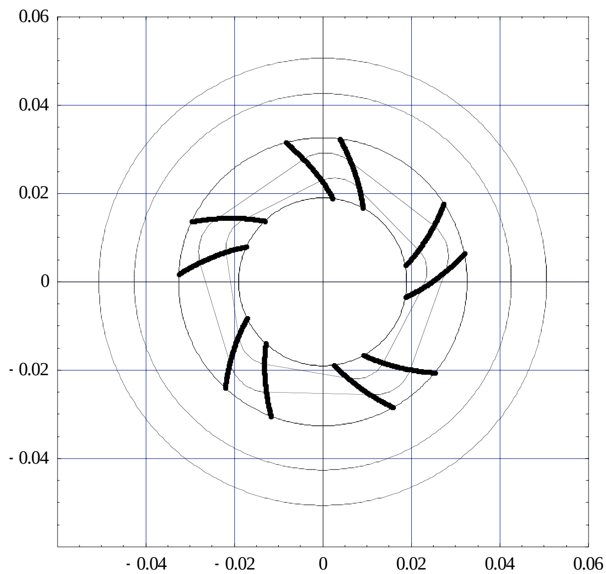

Figure 2: Magnetic pole shape of the spiral magnet.

$$B_{orbit} = B_0 \left(\frac{r}{r_0} \right)^k$$

$$B_{acc} = B_c \left(\frac{r_c}{r} \right)^2 + B_0 \left(\frac{2}{(k+2) r_0^k} \right) \frac{r^{k+2} - r_i^{k+2}}{r^2}$$

Figure 3 shows calculation results of beam envelope during acceleration. The figure shows that large beam size at the injection becomes small beam size gradually in time as the energy of particles increases. An extraction average radius can be selected with a parameter arrangement of B_0 and B_c.

A space charge effect around the injection energy is estimated with beam simulation as following method:

- Linear focus strength is calculated in each cell. Then beam envelope is calculated without space charge effects in each cell,
- Linear focus strength of space charge effect is calculated in each cell. Linear focus strength included the space charge effect is also calculated,
- Iteration until lattice parameters are not changed.

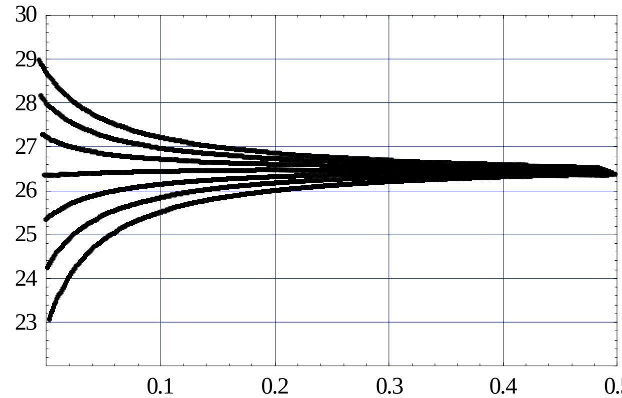

Figure 3: Beam envelope during acceleration: time [ms] in the horizontal coordinate, and average radius [mm] in the vertical coordinate.

Figure 4 shows tune spreads due to space charge effects as a function of peak beam current. Peak current 8 A can be accelerated if a tune spread 0.37 can be allowed. Average beam current is estimated about 5 micro A. We will use the laptop accelerator as an X-rays generator; X-rays irradiation, X-rays CT. An internal target is installed in the ring. The mechanism for generating hard X-rays with such a low energy ring is bremsstrahlung from a thin wire target placed in the extraction beam orbit .

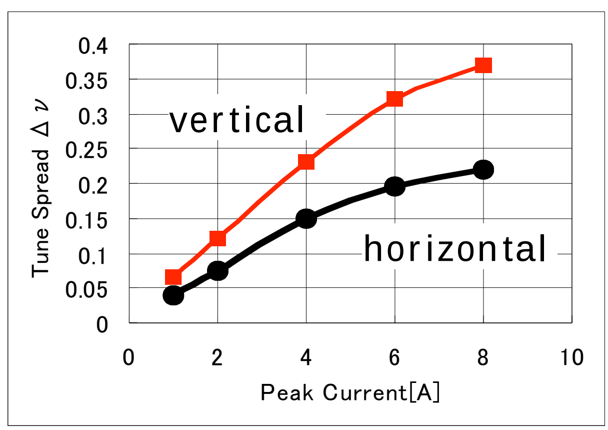

Figure 4: Tune spread due to space charge effects as a function of peak beam current: electron beam energy is approximated to be a 60 keV.

PROTO-TYPE SPIRAL SECTOR MAGNET

Proto-type five-sectors spiral bending magnet has been designed and constructed [2]. Outer diameter of the magnet is as small as 100 mm, and weight is about 2.8 kg. Basic parameters are shown in Table 2. The magnetic pole is made of MBS-318; Mitsubishi Materials bonded soft magnetic material, and several kHz repetition rate can be done because eddy current loss is very small. Magnetic power supply can be done with a simple IGBT solid-state amplifier. Figure 5 shows a photograph of the magnet. Figure 6 shows a photograph of the magnet divided into two sections. The spiral pole shape was easily shaved with end mills.

Magnetic field measurements were done with a hole probe. Figure 7 shows an example of an excitation curve of the magnet. A repetition rate of the magnet at the measurement was 400 Hz that was restricted from the power supply we had. Field mapping measurement were also done, and measured fields agreed well with the calculated fields, and rapid cycle repetition can be practicable.

Table 2: Basic parameters of a spiral sector magnet.

Diameter of magnet	100 mm
Height of magnet	80 mm
Total weight	2.8 kg
Magnetic field	0.59 T
Gap injection/extraction	7.5mm/5.4mm
Turns	7 turn/pole
Radii of pole	20.5 mm / 32.6 mm
Coil current	250 A
Inductance	0.072 mH

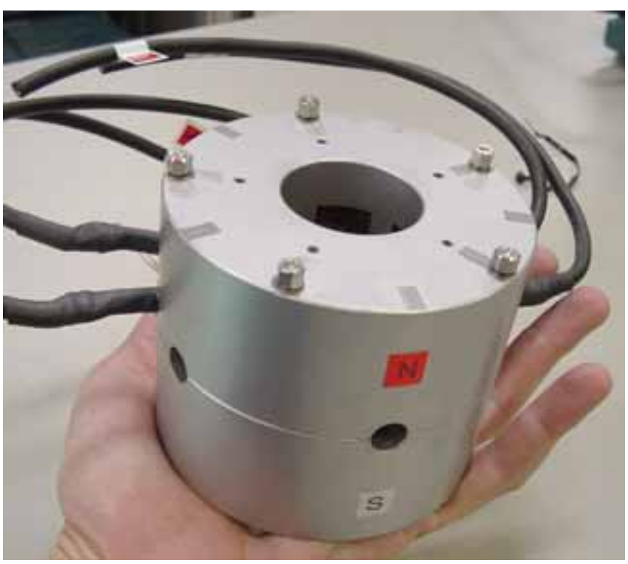

Figure 5: Photograph of the spiral-bending magnet of the laptop accelerator.

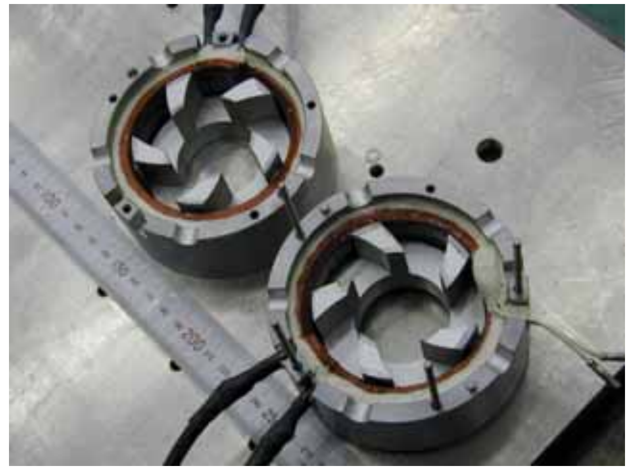
Figure 6: Photograph of the magnet divided into two sections.

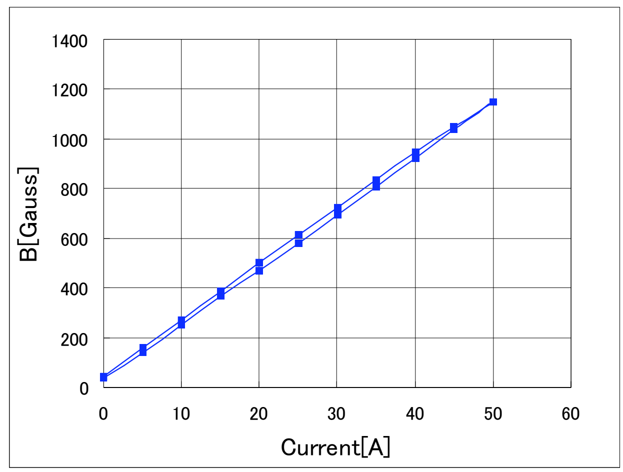

Figure 7: Excitation curve of the spiral-bending magnet.

CONCLUSION

A hybrid accelerator using an FFAG injection scheme is proposed. Both magnetic fields and closed orbits are changed in time as the energy of particles increases. A design of a compact induction electron accelerator, and a proto-type making of a spiral magnet show that the hybrid accelerator is suitable for industrial and medical applications in compactness and low price. Ion beam simulation studies of rf acceleration are to be published.

ACKNOWLEDGEMENTS

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REFERENCES

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[2] H. Tanaka, T. Nakanishi, “Design and Construction of a Spiral Magnet for a Hybrid Accelerator”, Proceedings of the 1st Annual Meeting of Particle Accelerator Society of Japan, (2004), p.465.