INDUCTION ACCELERATING DEVICES FOR INDUCTION SYNCHROTRONS AND THE SUPERBUNCH VLHC

K. Takayama, J. Kishiro, E. Nakamura, T. Toyama, KEK, Ibaraki-ken
S. Arakawa, Hitachi Metals, LTD., Shibaura
T. Hatano, K. Iida, Y. Imanishi, T. Sakuma, N.Shimizu, NGK, Nagoya
S. Naitoh A. Tokuchi, Nichicon Corporation, Kusatsu
K. Koseki, Sokendai, Tsukuba
K. Horioka, M. Nakajima, M. Watanabe, TIT, Nagatsuda

Abstract

Key devices for an induction synchrotron [1] and the recently proposed Superbunch Hadron Colliders [2] are a rapidly switched induction acceleration cell and its modulator. These induction acceleration devices and all solid-state power modulators are being developed under collaboration between KEK, Tokyo Institute of Technology, Nichicon, NGK Insulators, and Hitachi Metals. The modulator must switch a peak voltage of 2-3kV with a pulse repetition rate of 100kHz-1MHz. An effective pulse duration of 1msec is required for acceleration. At the same time, a shorter time-duration of 40-100nsec is required to generate a barrier bucket and to achieve a long superbunch. After careful core-loss measurements for various magnetic-core materials and selection of switching elements, several prototypes of the induction module and modulator have been assembled and successfully operated at 100kHz-MHz with a burst of 10pulses. Currently a practical device capable of being operated in the 1MHz CW mode is under assembling, which is being installed in the KEK 12GeV-PS. Its operational results will be presented at the conference.

1 INTRODUCTION

The high energy accelerators are continuously required to increase its beam intensity or luminosity for the many kind of particle experiments. The high intensity directly means the large charge density and causes a lot of defects coming from the strong space-charge effect. The RF accelerator always encounters the problem coming from the high charge density, which generates the beam loading current and several level of beam feed back or feed forward system are required. The high space charge induced resonance, for instance, enhances the betatron modulation additional to the normal lattice function.

We proposed[1] a means of making a long bunch and of accelerating the bunch keeping its length long. In this scheme, the long bunch, which is extendable up to about 90% of the accelerator circumference, is realized by employing the barrier bucket technology and accelerates long bunch by using a pulsed devices such as induction accelerator unit. The "superbunch" is an extremely long bunch, which occupies almost of the accelerator circumference. The superbunch is, for instance, a kind of a sausage like long bunch in contrast to the beans like bunch forming by the sinusoidal RF voltage. And the charge density in the superbunch is easily possible to keep low even if the integrated charge is increased.

The proposed induction synchrotron(IS) has to have two sorts of induction pulse devices. One sort with a short time-duration and a high integrated-voltage generates the so-called barrier bucket, which captures an injected bunch or stacks a superbunch. The other with a long time-duration and a medium integrated-voltage simply accelerates the superbunch. The required integrated-voltage, pulse-duration, and repetition rate depend on each accelerator. These parameters are determined by the momentum acceptance, ramping profile of the guiding field, and revolution period along the accelerator. Fortunately, the integrated inductive voltage linearly increase by stacking units serially in space and the required time-duration is realized by stacking units serially in time. For a while a basic specification on the single induction unit is supposed that the induced voltage is 10kV and the pulse duration is 500nsec for acceleration and 40-100nsec for the barrier bucket. Thus, the experimental demonstration of such unit with rep-rates of MHz is crucial to discuss a feasibility of the induction synchrotron.

We have no sufficient information of CW high rep-rate operations of this kind of induction unit. Our main concerns are listed below,

(1) heat dissipation in the magnetic core and switching elements,
(2) jitter in the output voltage and in time,
(3) life of the switching element,
(4) charging voltage and trigger-timing control for desired acceleration.

In order to make these issues clear, a systematic study program is being conducted under the above collaboration.

2 LOSS IN THE MAGNETIC CORE

The most serious problem is the heat dissipation in the magnetic core. Because the induction acceleration unit has to be energized of high rep-rate of about 1MHz.

The heat dissipation in the core is dependent on the core material and it strongly varies with the excitation current rise time and the maximum voltage swing. The full excitation is usually measured and some are sited on industry catalogues. However, in the IS, the induction units is excited at extremely high repetition rate. The core loss must be low, otherwise the thermal degradation of the magnetic characteristics is troublesome. To mitigate the core loss as small as possible, the core operation in the minor-loop seems to be desired. However, the characteristics of the minor-loop operation have not been known well.

A test stand to measure the core magnetic behaviour has been set up, and the core loss variation for the different excitation rate was observed. Figure 1 shows the measured B-H curves for two sorts of core material.

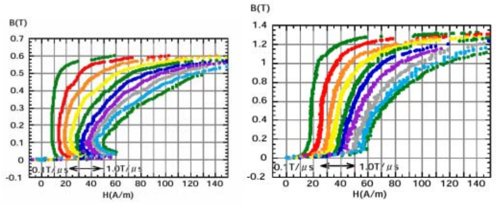

Figure 1: Measured B-H curve. Right: Co-amorphous core, Left: Hitachi FINEMET

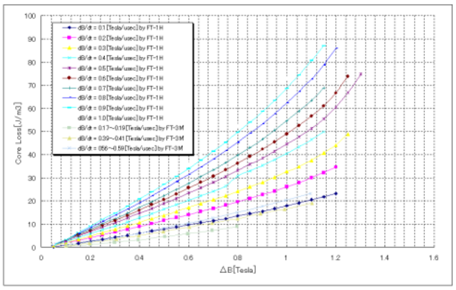

Figure 2: The core loss dependence on the magnetic field swing and swing rate.

These raw data were analysed and the core loss dependence on the excitation rate was obtained. Figure 2 shows the analysed results of the core loss.

The magnetic swing, DB, in our design should be restricted within 0.2Tesla, which is available level of the core loss by some coolant flow.

Table 1: The estimated head deposit in an induction unit, if it is installed in the KEK 12GeV PS.

Voltage: *V*0 (kV)	2.5
Pulse Width: τ (ns)	450
Rep. Rate (kHz)	888
Duty Factor	0.6

Core

Material	FINEMET FM-3M			
ID: *r*1 (mm)	225			
OD: *r*2 (mm)	390			
Width: *w* (mm)	10			
Cell length (m)	0.1			
No. of core: *N*	3	4	5	6
Volume (m^3)	2.39E-3	3.19E-3	3.98E-3	4.78E-3
Max Inductive current: I_0 (kA)	44.4	42.5	41.46	40.79
(kΩ)	8.8	9.2	9.4	0.0
Max field deviation: *dB* (T)	0.45	0.337	0.27	0.22
Field swing rate: *dB*/*dt* (T/μs)	1.00	0.75	0.60	0.49
Full Swing loss (J/m^3)	47.68	37.83	31.68	26.89
Minor Loop Loss (J/m^3)	9.71	4.99	3.00	1.87
1 Pulse loss (J)	0.0232	0.0159	0.0119	0.0090
Loss/Cell (Include. Duty) (kW)	12.4	8.5	6.4	4.8

3 COOLING SYSEM DESIGN

The heat dissipation in the core is estimated by taking the core loss data, mentioned above. Table 1 shows an example of the estimated heat dissipation in an induction unit in case of KEK 12GeV PS.

Number of magnetic cores in an unit is determined by considering the inductance, which maintains the voltage droop within the superbunch length, and the maximum field swing is strongly restricted less than 0.2T at least. So that the typical heat dissipation is around 5kW, and an efficient cooling system need to be designed.

The efficiency of the cooling system should be carefully examined. Because the induction unit is fundamentally a high voltage pulse device so that not only the cooling channel design but also the electric insulation structure need to be taken into account, simultaneously.

The cooling channel was modelled by employing the computer code ANSYS, and the coolant flow was simulated as shown in figure 3.

The coolant is put into from the upper-left port and flows down to the lower-right port. The half circle is the modelled magnetic core. Also the temperature rise under the modelled coolant flow was estimated (figure 4).

A water-cooling vessel was examined aiming to certify the model calculation (figure 5).

Several thermocouple of Cu-Constantan were attached on the heater and water channel, and the agreement between the ANSYS simulation and the measurement were quit good.

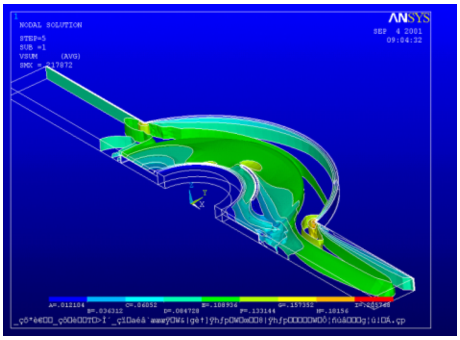

Figure 3: ANSYS model of the cooling channel.

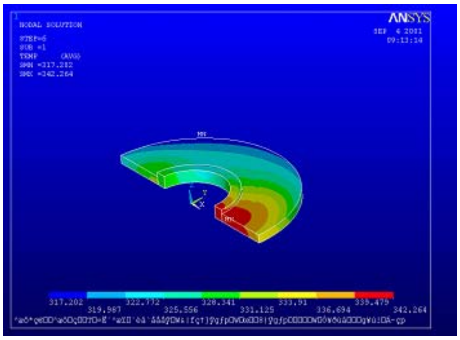

Figure 4: Temperature distribution on the core surface, ANSYS model.

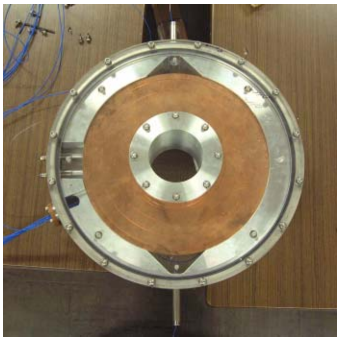

Figure 5: 3kW electric heater test cooling vessel.

4 DEVELOPMENT OF THE HIGH REP-RATE HIGH VOLTAGE MODULATOR

We carefully examined several kinds of solid-state switching element according to its switching speed, current capability and on/off resistance. And also the capacitance between the electrodes is a key parameter to achieve fast characteristics in the pulse device. Field effect transistor (FET) is one of the candidates for the high rep-rate modulator. The other element is the static induction thyrisotr (SITh), which is now developing in Nihon Gaisi Co.LTD and has a voltage/current capability beyond 4kV/1kA and provides a large through-rate. We are now developing a FET modulator, because of its availability in a commercial base.

The modulator has to have four switching circuits, two of which are prepared for positive excitation of the induction core and the other two are used to reset the core magnetic state.

A switching block consists of five FET in series and two in parallel. 2.5kV high voltage is stored in a capacitor and put into the induction core at an externally triggered timing. Figure 7 shows the inner structure of 2.5kV, 1MHz FET modulator.

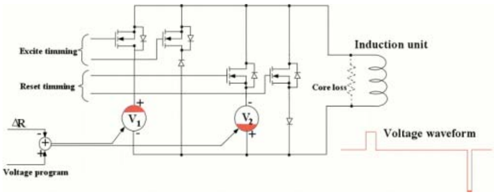

Figure 6: Block diagram of the FET modulator.

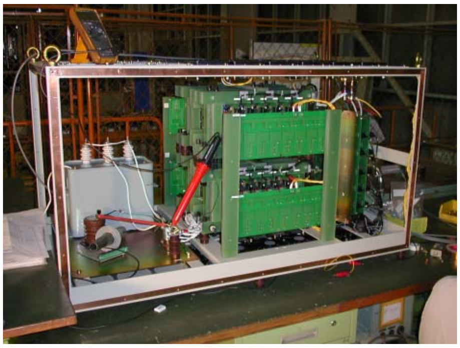

Figure 7: 2.5kV-1MHz FET modulator.

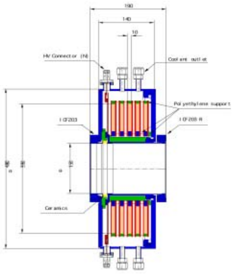

Figure 8: Induction unit.

5 CONCLUSION

The investigation on the core behaviour, switching devices and capability of the cooling system are almost finished. The induction acceleration unit of 2.5kV, 1MHz is now under designing as shown in figure 8. And the full test operation is scheduled by June 2002.

6 REFERENCES

[1] K.Takayama and J.Kishiro, NIM A451(2000), 304

[2] K,Takayama, J.Kishiro, M.Sakuda and M.Wake, Phys. Rev. Lett(2001)