HIGH BEAM CURRENT EXPERIMENTS FOR THE KEKB CONDUCTED AT THE TRISTAN ACCUMULATION RING

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Abstract

Dedicated machine time of about 10 weeks has been devoted to the high beam current experiment by using an electron beam of the TRISTAN Accumulation Ring (AR). In the experiment, we investigated performance of prototypes of RF cavity systems and a bunch-by-bunch feedback system which will be used in the KEKB. We found that the RF cavity systems work very well at the beam current more than 500mA. The bunch feedback system was very effective to suppress the instability. We also made an experiment on the fast ion instability with interesting results.

1 PURPOSE OF THE EXPERIMENT

The KEKB is an asymmetric electron-positron collider aiming at the study of the B meson physics and is now under construction at KEK. Main design parameters of the KEKB are listed in Table1.

	HER	LER
Beam energy	8.0GeV	3.5GeV
Luminosity	$1 \times 10^{34} cm^{-2} sec^{-1}$	
Beta functions at IP β_x^*/β_y^*	0.33/0.01m	
Tune shifts ξ_x/ξ_y	0.039/0.052	
Beam current	1.1A	2.6A

Table 1: Main design parameters of the KEKB

As is seen in the table, one of the most critical issues for realizing its design performance is accumulation of these unusually high beam currents against several obstacles.

One of the major beam current limitations will possibly come from coupled bunch instabilities arising from the fundamental mode and the higher order modes of acceleration cavities and some other sources such as resistive walls. To overcome the coupled bunch instabilities from RF cavities, we have developed two new types of RF cavity systems. One of these is a normal conducting cavity called ARES(Accelerator Resonantly coupled with Energy Storage) and the other is a specially designed superconducting damped cavity. We have also developed a bunch-by-bunch beam feedback system to suppress remaining instabilities.

The main purpose of the present experiment is to investigate whether these RF systems and the beam feedback system do work well under a high beam current. In the beam test conducted at the AR, we could prepare the beam current of 573mA at maximum.

In parallel with these beam tests, we also carried out machine studies on the fast ion instability and other coupled bunch instabilities, which resulted in some interesting information.

2 EXPERIMENTAL SETUP

2.1 AR

The AR was designed and had been employed for the injector of the TRISTAN Main Ring. When the TRISTAN project was terminated in 1995, the main role of the AR was switched to a SOR machine. Main machine parameters are listed in Table 2, including beam parameters used in the experiments. A 2.5GeV linac is used for the injector of the AR. Almost all present experiment was done at this injection energy, although usual SOR operation is done at 6.5GeV.

Particles	electrons
Circumference C	377m
RF frequency f_{RF}	508.58MHz
Harmonic number h	640
Beam energy E_b	2.5GeV
Beam current I_b	573mA(max)
Tune ν_x/ν_y	10.160/10.228
Momentum compaction α	0.0129
Natural chromaticity ξ_{x0}/ξ_{y0}	-14.5/-13.7
Chromaticity corrected ξ_x/ξ_y	~7/7
Radiation loss/turn U_0	0.1458 MeV
RF voltage V_c	0.6~2.5 MV
Synchrotron tune ν_s	0.018~0.036
Natural bunch length σ_l	2.0~0.94 cm
Energy spread $\Delta E/E$	4.40×10^{-4}
Damping time τ_e/τ_β	21.6/43.1 msec
Natural emittance ε_{x0}	43.6 nm

Table 2: Main machine parameters of the AR

The AR has two RF sections in the east and west long straight sections. Originally 4 units of 9-cell RF cavities called APS (Alternating Periodic Structure) were installed in each RF section. In the experiment, these APS type cavities were removed temporarily and the cavities for beam test were installed. The bunch-by-bunch feedback system was installed in the south long straight section.

2.2 ARES

The ARES is composed of three cavities; i.e. an accelerating cavity, a coupling cavity and a storage cavity. The storage cavity is intended to store large energy so that we can decrease the effective R/Q value of the cavity system and mitigate the coupled bunch instability arising from the fundamental mode. We have prepared two different types of the ARES for the beam test. They adopt different schemes for HOM damping of the accelerating cavities. For the first

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type of the ARES (ARES95), we adopted a chokemode-type accelerating cavity. The second type of the ARES (ARES96) is equipped with four rectangular waveguides and grooved beam pipes. In addition to these, an accelerating cavity of the ARES95 alone, which we call ARES-A, was installed in the east RF section in order to provide necessary RF voltage.

2.3 SCC

For a superconducting cavity (SCC) of the KEKB, we adopted single-cell structure, since it can reduce the number of HOMs and also minimize the coupler power. For the purpose of HOM damping, beam pipes with large diameters are attached on both sides of the single cell cavity. All HOMs are extracted to the beam pipes and absorbed by ferrite absorbers attached on the inner surface of the pipes. As for an input coupler, we adopted a coaxial antenna type coupler, which is the same type as was used for the TRISTAN Main Ring.

2.4 Bunch-by-bunch Feedback System

Prototypes of both transverse and longitudinal feedback systems were tested in the experiment. The transverse system consists of button electrodes for signal pickup, an analog signal processing system including a long cable delay, two kinds of power amplifiers which cover different frequency regions and stripline electrodes used for kickers. The longitudinal system is composed of button electrodes for signal pickup, a digital signal processing system including a 2-tap FIR filter, power amplifiers and a four cells of series-drift-tube type kicker which is just the same as used in ALS.

3 MACHINE OPERATION

3.1 Schedule

The experiment was done in two periods except some preliminary beam experiments. The first experiment was carried out during the period from July 1st to July 22nd in 1996. In this experiment, we only tested ARES-A and a full system of the superconducting cavity. As for the feedback system, only the transverse feedback in the horizontal direction was tested.

The second experiment was done during the period from October 17-th to December 2nd. In this experiment, two sets of full-set ARES (ARES95 and ARES96) were installed and examined with the beam. In this report, we mainly describe results of the second experiment and mention briefly the first experiment when necessary.

The study time of the second experiment consists of about 7 weeks. For the first 4 weeks of the study, we operated the ARES96 in the west RF section and ARES-A in the east. And for the next two weeks, all normal conducting cavities in the ring were detuned and SCC was operated and studied. For the last week of the study, we operated SCC and the ARES95. In Table 3, we summarize study or operation items and the number of shifts consumed for each item. Here, we mean 8 hours by 'shift'.

Study or operation item	# of shifts
ARES96	16.5
ARES95	4
SCC	20
Feedback	9.5
Fast ion instability	7.5
Multibunch instability	4.5
Other studies	1
SCC warmup	14
ARES95 aging	16.5
Machine tuning	4
Trouble	13.5
Gas desorption from vacuum chamber	19.5
Linac study and maintenance	26

Table 3: The operation statistics in the second experiment

3.2 Preparation of High Current Beam

A crucial mission to the beam operation was to accumulate as high beam current as possible. In the following subsections, we describe experiences on problems which we encountered in the course of the beam operation.

3.2.1 Beam lifetime

Prior to the experiment, we installed lots of devices for the beam test in the ring. Owing to this, vacuum pressure of the ring was rather bad particularly at the beginning of the experiment. In this situation, the beam lifetime which is determined by the collision of the beam with residual gas was very short and the beam current was limited by the balance between the particle loss rate due to the beam life and the injection rate.

To improve this situation, we had to rely on the photo-desorption process of the vacuum chamber induced by synchrotron radiation. For this purpose, we merely circulated the beam without any other studies. The number of shifts used for gas desorption amounted to 19.5 in total. Most of these were concentrated in the beginning of the experiment. The effort to improve vacuum pressure continued until the middle of the experiment when beam lifetime did not limit the beam current anymore.

3.2.2 Coupled bunch instability

In the beam test, we encountered unexpectedly strong coupled bunch instability. Strength of the instability depended on the beam filling scheme. In the experiment, we tried three different kinds of filling schemes, i.e. (1) bunch train scheme, (2) equally spaced multibunch scheme and (3) 4×4 filling scheme.

In the bunch train filling scheme, we tried to inject a beam with a bunch spacing of 2nsec. This bunch spacing is minimum with our RF frequency of 508MHz. We tried three cases for the bunch current; i.e. 1mA/bunch, 2mA/bunch and 4mA/bunch. When we did not use the beam feedback system, the maximum beam current was around 40mA in the case of 2mA/bunch, for example. However, by using the transverse feedback system the total beam current was increased to 320mA. Both the horizontal and vertical feedback were needed to store high current.

The equally spaced multibunch filling scheme was mainly used for the study on the coupled bunch instability itself. Results of the study are summarized briefly in the next section. Also in this mode, large beam current could not be stored without the feedback system.

The bunch train injection and the equally spaced multibunch mode were needed for some study items, such as the study on the fast ion instability or the study on the coupled bunch instability itself. However, other studies required as a high average beam current as possible. To meet this requirement, the optimum beam injection condition has been searched. Through trial and error, we found that we can store more than 500mA with so-called 4×4 injection scheme. In this scheme, we inject four bunch trains which are equally spaced. Each bunch train consists of four bunches and then the total number of bunches in the ring is 16. The bunch spacing in the bunch train is 40nsec which means 20 RF buckets. In addition to this injection scheme, we used relatively high values for corrected chromaticities of 7 both for ξ_x and ξ_y so that we can rely on the head-tail damping.

3.2.3 Heat-up of hardware components

The AR was not designed for a high beam current machine. We paid very close attention to heat-up of hardware components. Particular attentions were paid to the bellows, gate valves and ceramic chambers for pulse magnets or beam current monitors. Temperature sensors were attached on all of these components and temperature was monitored in realtime and recorded with a logging database system together with values of vacuum pressure all around the ring. In the first experiment, we observed conspicuous temperature rise for some ceramic chambers and one of these induced vacuum leakage just before the end of the experiment. Before the second experiment, these were replaced with spares. In the second experiment, the components listed above did not give us any troubles. However, we were troubled with heat-up of the stripline electrodes which were used for beam feedback system in the usual operation and were not used in the experiment. Owing to this heat-up, one of the electrode was deformed to block off the beam motion. We removed all relevant electrodes. Based on the bench test after the beam experiment, we guess that heat-up was triggered by radiation damage of cables which connected the electrodes and dummy loads for power attenuation[1].

4 RESULTS

Results of the experiment for each study item are reported in detail elsewhere[2][3][4][5][6][7] [8][9]. In this report, a very brief summary is given below.

4.1 ARES

The two ARES systems were tested independently to each other; when one ARES was operated, the other ARES was detuned. Most of the study was concentrated on the ARES96, which was considered to be adopted as the normal conducting cavity for KEKB. The ARES96 was operated for about 4 weeks and the ARES95 for 2 days. In order to provide necessary voltage, ARES-A or SCC was also operated together with the ARES.

4.1.1 High power and high current operation

Main RF design parameters for the ARES in KEKB-LER are: 0.5 MV of accelerating voltage which corresponds to a wall dissipation of 155kW, and 350kW of input power with full design current. Prior to the beam experiment both ARESs were successfully tested above 200 kW of the wall dissipation. In the beam test, a beam current of 500mA was stably stored by either of the two ARES cavities operating at 0.5MV together with SCC or ARES-A.

Two input couplers with a disk-type ceramic window were broken at about 70kW just before the beam test. After replaced with a spare, we conditioned it more carefully by having harder interlocks and keeping better vacuum pressure. This coupler was successfully operated up to 200kW during the beam experiment. In a bench test performed after the beam experiment, it was shown that this type of coupler works well with an input power of 430kW.

4.1.2 Fundamental mode behavior under heavy beam loading

Since the ARES is a highly original scheme, its basic characteristics of the fundamental mode with heavy beam loading was carefully studied. We observed behavior of the ARES system with changing beam current, beam fill pattern, relative phase between the ARES and another cavity (ARES-A or SCC) or a voltage ratio of the two cavities. Observed behavior was well reproduced by calculations based on a coupled-resonator model. In particular, following two points are important. First, the movement of the tuners at the accelerating and storage cavities under beam loading was in good agreement with a calculation. It indicates that the frequency detuning of the fundamental mode is reduced as was expected. Second, we observed transient behavior of the power extracted from the damper at the coupling cavity which damps parasitic 0 and pi modes associated with the fundamental mode. The measured responses to a single bunch beam, an equally-spaced beam, and an equally-spaced beam with an ion-clearing gap were pretty well reproduced by simulations. Thus the principles of the ARES theory were experimentally confirmed.

4.1.3 HOM damping and absorbers

The maximum power absorbed by the HOM absorbers was about 6.6kW per cavity for the ARES95 and about 6.4kW for the ARES96. So far as these power is concerned, there was no problem in HOM power absorption.

The effect of HOMs on the beam was studied by scanning the movable tuners at the accelerating and storage cavities of the detuned ARES with a 100mA single bunch beam. During the tuner scans, there was no indication that the HOMs affected the beam motion. In the other studies during the experiment, we did not see any indication that the HOMs are responsible for the beam instability.

4.1.4 Long-term stability

The ARES96 was operated for about 4 weeks. During this term, we consumed lots of shifts for gas desorption of the vacuum chambers. In some cases, we continuously held overnight a high beam current more than 400mA. Even in such a relatively tough condition, the ARES did work very stably.

4.2 SCC

The SCC was operated for one week in March, two weeks in July and two weeks in November in 1996. Most of the time it was operated at 1.0 - 2.5MV and all other cavities were detuned except for the tuner scan study.

4.2.1 High current and high field operation

The results of the beam tests with the SCC exceeded the world records set by a CESR-B SC cavity tested in the CESR ring as follows. The maximum beam current of 573mA was stored by our cavity operating at 1.2MV. A high current of 350mA was also stored at 2.5MV, which is much higher than the design voltage of 1.5MV for KEKB-HER. The current limitations were not by cavity performances, but by other things such as saturation due to a balance between the beam life time and the injection rate (the case of 1.2MV), or heat-up of ring components (the case of 2.5 MV). The maximum RF power transferred to beam was 160kW with an input power of 270kW. Furthermore, at a bench test performed prior to the beam test, an input coupler was successfully tested up to 850kW.

4.2.2 HOM damping and absorbers

The maximum HOM power absorbed by the ferrite absorbers was 4.2kW. We experienced no degradation of performance of the HOM absorbers during the experiment. The loss factor estimated from the absorbed power is consistent with a calculation at a bunch length of 1.5cm and longer.

Tuner scan was done at the beam current more than 400mA. We could not see any effects of the HOMs on the beam motion. In the tuner scan, we surveyed a frequency range of about 400kHz for the fundamental mode.

4.2.3 Direct RF feedback

The SCC control system was equipped with a direct RF feedback loop. We observed that it was very effective to stabilize the cavity control loops. When we stored 500mA without the direct RF feedback, there was a strong 0-mode coherent synchrotron oscillation. By applying the direct RF feedback, however, the oscillation was suppressed by 10dB and the beam current of 573mA could be stored stably. It mitigated the stability condition for the static Robinson phase instability.

4.2.4 Long-term stability

One critical issue is a trip, which is a discharge caused by condensed gas on cold surface of the SC cavity and the input coupler region. In the first beam test (July), the SCC could not be operated stably due to frequent trips. At that time vacuum condition of the AR was too bad, since we had opened a large part of the ring to install hardware components to be tested. Prior to the second experiment, we took two measures for this; i.e. (1) We increased the number of vacuum pumps from 2 ion pumps to 5 NEG plus 1 ion pump on each side of the SCC. (2) We installed an equipment to supply a DC bias between the inner and outer conductor of the coaxial-type input coupler. In addition to these, we warmed up the SCC to room temperature after the 4 week operation of the ARES96 and before the study of the SCC in order to degas the condensed gas. As things turned out, the frequency of the trips drastically decreased even without the DC bias and stable operation continued for two weeks during the second experiment. We guess that the improvement of vacuum pressure contributed to this. It is estimated that the gas flow rate to the cavity from the ring was reduced by one order by strengthening the vacuum pump power. Then, we could not investigate the effect of the DC bias.

4.3 Beam Feedback System

In the bunch train filling scheme, the transverse feedback was very effective, as is briefly mentioned before. Table 4 shows a summary of the maximum number of bunches stored in this mode depending on the feedback status and the bunch current. H (V) in the table designates the horizontal (vertical) feedback. The bunch spacing was 2nsec for these data.

Bunch current	H:off V:off	H:on V:off	H:off V:on	H:on V:on
1mA	18	20	-	$>$300
2mA	20	70	20	$>$170
4mA	25	25	60	$>$100

Table 4: Maximum number of bunches stored in the bunch train filling scheme.

In the case of 4mA/bunch, we could store 376mA at maximum, while we could not store 100mA without the feedback. The feedback system worked well with this short bunch spacing of 2nsec as well as with longer bunch distances. Damping times of the feedback were measured by employing the memory function of the two-tap FIR filter complex. Results were less than 1msec for the horizontal plane and about 2msec for the vertical direction at the bunch current of 2mA, which are consistent with expected values from a rough calculation.

On the other hand, we observed a strong coupled bunch motion also in the longitudinal direction. The longitudinal feedback system was effective to suppress the instability, although the feedback gain was not sufficient in some cases. However, the longitudinal coupled bunch instability was not responsible for the beam current limitation. A possible explanation for this longitudinal motion is that it originates from the bellows which do not have an inner shield. There exist about 130 such bellows in the AR.

4.4 Multibunch instability

To investigate the coupled bunch instability, we tried the all RF bucket filling scheme. In this scheme, we filled all of 640 RF buckets with the beam by injecting beam at a very low injection rate, typically in units of 20μA/bunch. This measurement was mainly intended to search high Q modes responsible for the coupled bunch instability. The total beam current was limited at around 20mA with this filling mode. However, no sharp betatron or synchrotron side band was observed at the maximum beam current. What we observed instead were vertical betatron side bands which were broadly distributed in a range of $\pm$20MHz around $n \times f_{RF}$, where n is an integer and f_{RF} the RF frequency. This indicates that the phenomena are related to the ion trapping.

To focus on the ion trapping effect, we made a further study with a symmetrical 64 bunch mode for the sake of the time saving. In this study, we used the transverse feedback system to hold the beam against the instability. We observed what happens when the feedback is turned off. By using the two-tap FIR filter complex again, the transverse positions of every bunch were recorded turn-by-turn for 1640 turns. The data taken was processed by FFT to see the beam spectrum and its time development. We found that the m=12 mode is most unstable at the total beam current of 80mA and the m=13 mode at 110mA, although some broadly distributed modes were excited. These results are qualitatively well reproduced by a calculation based on the 2-beam model. We guess that the beam current limitation in the equally spaced multibunch filling scheme comes from the ion trapping effect from these observations.

The current limitation in the bunch train mode, however, can not be explained by the conventional ion trapping effect, since most of the RF buckets are left unoccupied by the beam and the ions should be cleared during this long gap. A calculation shows that the fastest growth of the coupled bunch instability comes from the resistive walls and its growth time is around 7msec at 500mA if cancellation does not work. However, this growth rate is not enough to explain the maximum current shown in Table 4. It was observed that the beam loss due to the instability was coincident with the beam injection timing. This indicates that the transient effect of the coupled bunch instability should be taken into account. Further study is needed to understand the origin of this current limitation.

4.5 Fast ion instability

In the study, a bunch train of 100 bunches with the 2nsec spacing was stored, which means that only about successive 1/6 RF buckets were filled with electrons. Although we studied two cases for the total beam current of 115mA and 170mA, the two cases gave essentially the same result. We observed that the vertical coupled bunch oscillation was enhanced by introducing a nitrogen gas into the ring. This indicates that the phenomena are ion-related. The oscillation amplitude increased along the bunch train from the head to tail of the train. On the other hand, the oscillation phase decreased along the train. The growth time of the instability was shorter than several msec. These results can be interpreted as the fast ion instability. The total (oscillation) phase shift from the head to tail of the train was about 3 radians, which is consistent with a calculation based on the linear theory within factor 3. Further simulation studies based on more realistic model have been in progress.

5 FUTURE PROSPECTS

The test results encourage us to use the ARES in LER and HER, and the SC cavities in HER by keeping good vacuum environment. In FY1997 we started mass-production of the ARES and the SC cavities.

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