MICROWAVE INSTABILITY AT TRANSITION CROSSING IN THE KEK-PS

K. Takayama, D. Arakawa, J. Kishiro, K. Koba, T. Toyama, and M. Yoshii
High Energy Accelerator Research Organization (KEK)
1-1 Oho, Tsukuba, Ibaraki 305 Japan

Abstract

Microwave instability in the KEK proton synchrotron was systematically studied Temporal evolution of the microwave instability was clearly explained with a proton-klystron model. Beam position monitors and cavity-like vacuum chambers have been idetified as its driving sources. Replacement of these high impedance materials has been confirmed to reduce the growth of the instability to the expected level.

1 INTRODUCTION

The KEK 12GeV PS has been subject to serious damage of the microwave instability (MI) at transition crossing (TC) since the beginning of its operation[1]. Since KEK-PS's impedance budget has been never concerned, a lot of high impedance materials as discussed later are *periodically* located along the ring, following lattice components. The observed threshold beam current for the M.I. and size of Landau daming due to γ_t-jump are different in order of magnitude from that of the theoretical estimation based on the existing broad-band model. In the recent article[2], simulation works and experimental test of the longitudinal impedance, extensive beam experiments of the MI at TC, a proton-klystron model capable of consistently explaining the experimental results, and their comparison was presented. In the last summer, two-thirds of resonant impedance devices to which the MI can be attributed has been replaced by low impedance ones. Its results will be reported in addition to brief review of the article [2].

2 EXPRIMENTAL RESULTS

A single bunch(500MeV) from the booster ring was injected into the 12GeV-PS ring waiting with standing RF-buckets of harmonic 9. The beam intensity(1-5x10^{11} /ppp) was controlled by changing the H^- beam spill-length hitting a stripping carbon-foil in the booster, the RF frequency is ~7MHz, and the synchronous phase is switched from 15^0 to 165^0 at TC. To elucidate the dependence of the MI on phase-mixing speed, the size of γ_t-jump, $\Delta\gamma_t$, was varied up to 0.25 for 0.5msec Longitudinal bunch information was a signal from the fast wall-current monitor with ~2GHz resolution.

The MI observed in the KEK-PS always grows from the tail portion. Fig.1 shows a typical evolution of the bunch-shape which is projected on the time-axis. Below transition the MI never evolves to an observable level, just after TC it dramatically starts to grow within 1 msec near 1GHz, then a fraction goes away from the bunch-center. High frequency(400MHz-12GHz) components of the beam-induced signal on the vertical plate in the beam position monitor(BPM) were obtained by a spectrum analyzer; the 1.23GHz component is remarkable after TC when the instability occurs. This component is related to the MI and its frequency is in agreement with the modulation frequency observed in the bunch profile.

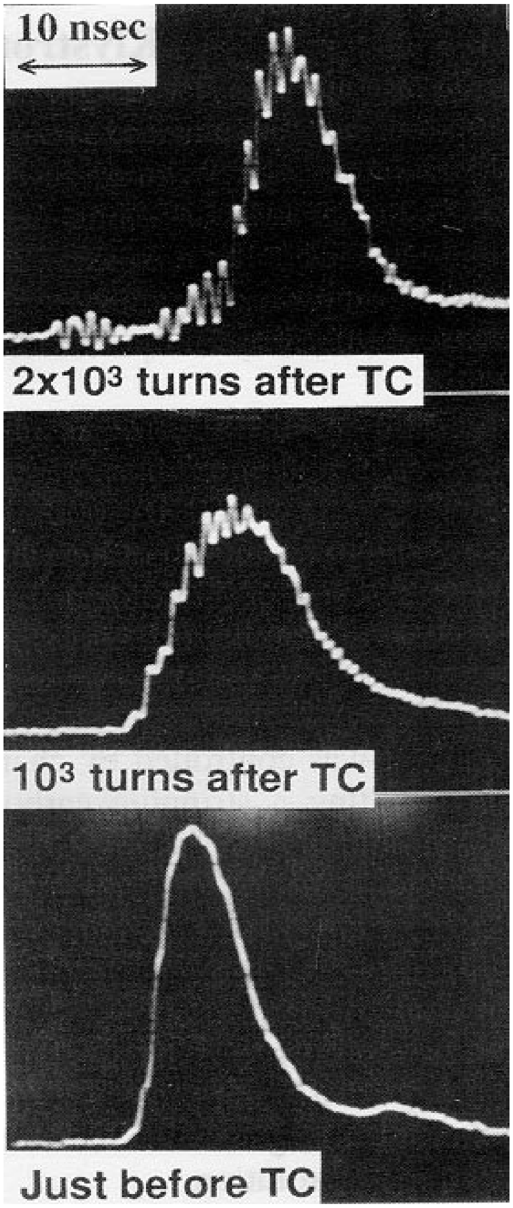

Fig.1. Bunch Profiles from -1 msec to +2msec
(t=0 msec: transition)

Fig.2 shows the ratio as a function of the particle number per bunch. Beyond some critical value of particle number the blow-up becomes obvious. The dependence of the emittance blow-up on a size of γ_t-jump is depicted in Fig.3 for a fixed beam current of N=5x10^{11}.

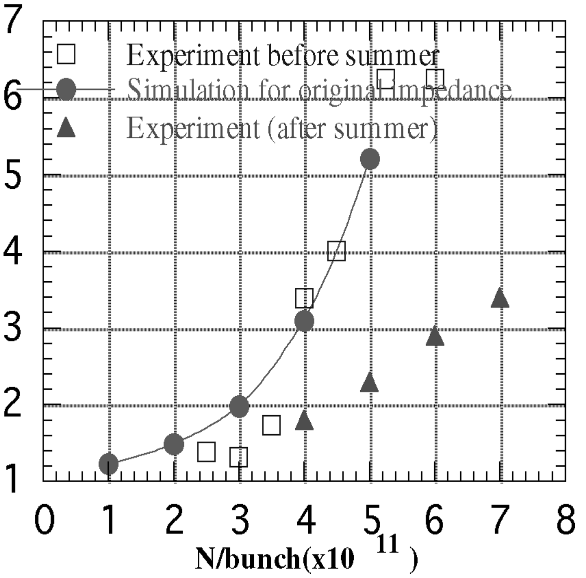

Fig.2. Emittance blow-up ratio vs the number of particles

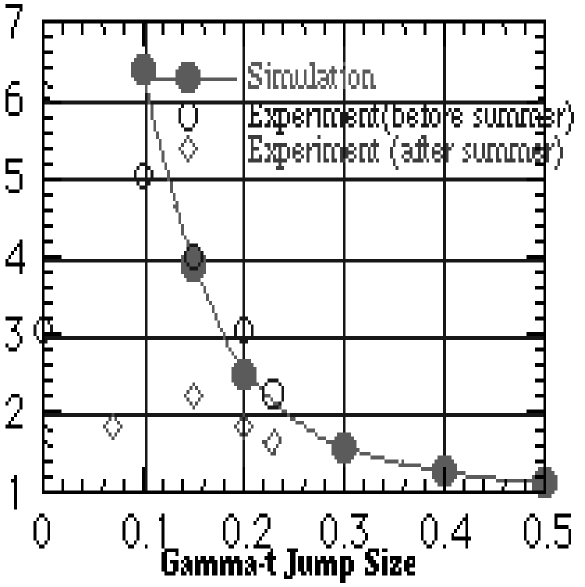

Fig.3. Emittance blow-up ratio vs the size of γ_t jump($\Delta\gamma_t$)

3 IMPEDANCE CALCULATION & MEASUREMENTS

Resonant structures(RS) capable of exciting the observed MI have been identified as a result of MAFIA calculations and impedance measurements at the test-bench. As shown in Table, the BPM and cavity-like vacuum-chamber(CVC) which are placed at each side of vacuum chamber in the lattice quadrupole magnets have a large shunt-impedance. In the numerical simulations, a magnitude of R_{shunt}/Q obtained by the MAFIA calculations and measurements has been used, which are in agreement to each other in order of magnitude; while the quality factor was treated as a kind of free parameter because a loaded Q in the actual ring is not satisfactorily estimated.

Table 1
Resonant Impedance(measurement/calculation)

	$\omega_\lambda/2\pi$ (GHz)	Q	R_{shunt} (Ω)	R/Q (Ω)
BPM	0.636/0.667	77/2650	1.5x10^3/2.6x10^4	19.4/9.8
	/1.13	/3769	/6.2x10^4	/16.3
	1.498/1.377	230/8222	5.3x10^3/3.3x10^3	23/40
CVC	/1.44	/4846	/1.4x10^5	/28.8
	/1.84	/4048	/1.9x10^5	/46.6

4 PROTON-KLYSTRON MODEL

In the model highly RS are periodically distributed along the beam-path and wake fields excited by the bunch-head can affect the bunch-tail. Member change in a global-scale between the bunch-head and -tail scarcely occurs near transition. All of excited RS can be regarded as idling cavities. Build-up of the wakes in each RS is treated in a formulation of the forced excitation of a damped harmonic-oscillator, as discussed in the reference [2].

5 SIMULATION RESULTS

The temporal-evolution of a bunch was numerically obtained. As seen in Fig.4, the simulation reproduces the essential aspects of the experimental result: (1) no notable growth of the MI below TE, (2) its rapid growth just after the TC, (3) run away of a bunch-fraction, and (4) large blow-up of the emittance after the TC-process.

General features of the MI are (a) efficient energy transfer from beam to microwaves is resulted from the deceleration of the micro-structure's core, yielding the drift of the cores in the negative direction of the momentum space, (b) the interaction between wakes and the beam tends to occur in the bunch-tail owing to the finite Q-value, (c) the convection of the micro-structure formation toward the bunch-head is crucial from the same reason as that of (b). According to (b) and (c), the particles located in the region of $E>E_s$ and $\phi>\phi_s$ below the TE and $E<E_s$ and $\phi>\phi_s$ above the TE can contribute to the evolution of the MI. Since the wake's phase coincides with the motion of micro structure's core, the particles located in the other side of momentum-space are affected by the wake in counter phase, suffering a rapid modulation in their motion. Below the TE a fraction of decelerated microbunch core necessarily falls into the region of $E<E_s$ where the fraction is forced to move in the opposite direction of the phase ϕ; the microbunch formation is likely to be wiped out. Thus the MI is not able to evolve to a level comparable to that above the TE.

In the early-stage (≤400 turns) bunching and amplification proceed like that in a microwave amplifier such as free-electron lasers; the repeated synchrotron-rotation in the micro-bucket doesn't occur but particles almost drift in the momentum-space. A fraction of the micro structure placed in the decelerating phase is rapidly decelerated, amplifying the microwaves. The microwaves' phase follows the motion of the decelerated fraction because electro-magnetic waves are amplified at the expense of the kinetic energy of protons. Consequently the other fraction having been placed in the accelerating phase falls into the decelerating phase to turn to contribute to further microstructure formation. This looks like eruption in the bunch-tail (see the middle of Fig.4).

Simulation results indicated that for the fixed value of $R_{shunt}/Q=10$ ohm and $(\Delta\gamma_t)=0.15$ the bunch eruption due to the MI is remarkable beyond $N_0=3x10^{11}$ as seen in Fig.2. Simulations showed larger suppression of the MI as the size of $d\gamma_t/dt(=2(\Delta\gamma_t)_{max}/\Delta t)$ increases (see Fig.3) and are in good agreement with the experimental results. The fast phase-mixing in a case of the large $(\Delta\gamma_t)_{max}$ is likely to prevent the MI from growing up. There is a notable difference in the region of small size of $d\gamma_t/dt$ where the nonlinear kinematics effects are dominant and a beam bunch asymmetrically stretches in the direction of $\Delta p/p>0$. There the momentum spread in the bunch tail exceeds the momentum aperture; accordingly a significant fraction of the bunch tail is lost. To confirm the relative importance of the broad-band space-charge impedance in the present MI, space-charge forces were turned off; there any notable change in the eruption-like feature was not found.

6 RESONANT IMPEDANCE REDUCTION

During the summer shutdown, the two-thirds of highly resonant impedance device pairs (BPM and CVC) have been replaced by newly designed ones. The new BPM is an elctrostatic type. Its R_{Shunt}/Q is reduced by a factor of 2 or 3 according to the MAFIA calculation. The resonant frequency of the dominant mode moves to 342MHz. In the new CVC the original cavity-like structure is discarded and the evacuation port is shilded by RF slits. As a result, a magnitude of resonant impedance is neglible small. The emittance blow-up ratio has been measured in the same way. The results are put in Figs2,3. Certainly, the emittance blow-up ratio has notably decreased as expected, although the MI itself is still observed to evolve at some level.

7 CONCLUSION

The systematic experimental results of the MI at TC and their theoretical explanation were presented. The countermeasure employed to suppress the MI was reported. The particular aspects of eruption-like breakup just after TC and its evolution from the tail-half which have never been anticipated by the conventional collective instability theory and simulation where a cumulative feature of the beam-cavity interaction in a finite time-period is not taken into account, were clearly manifested by the proton-klystron model. The TC in the KEK-PS may provide the germinal situation of a large-scale proton klystron which was proposed as a possible power source for linear colliders[3].

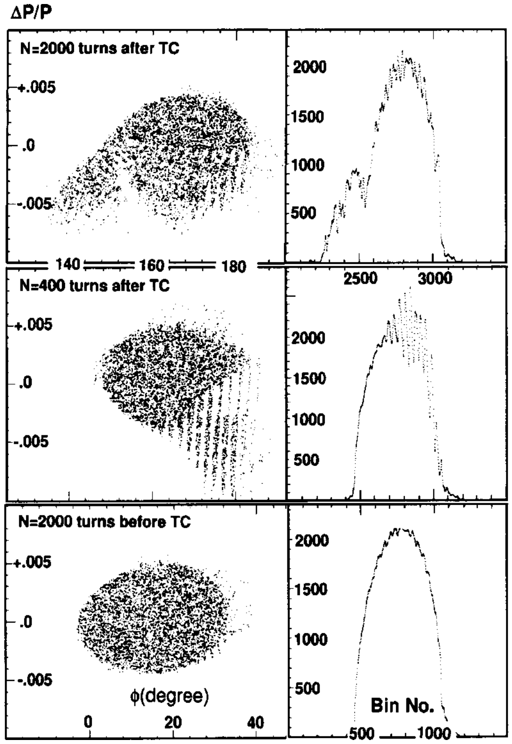

Fig.4. Typical simulation results of TC

8 ACKNOWLEDGEMENTS

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9 REFERENCES

[1] Y.Mizumachi and K.Muto, *IEEE Trans. on Nucl. Sci.* **NS-28, No. 3**, 2563 (1981), S.Ninomiya and T.Ieiri, private communication (1995).
[2] K.Takayama, D.Arakawa, J.Kishiro, K.Koba, and M.Yoshii, *Phys. Rev. Lett.***78**, 871 (1997).
[3] E.Perevedentsev and A.Skrinsky, *Proc. of 12th Int. Conf. on High-Energy Accelerators*, 508(1983).