

# PULSED OPERATION OF THE 972 MHZ PROTOTYPE CRYOMODULE FOR ADS SUPERCONDUCTING LINAC

E. Kako<sup>#</sup>, S. Noguchi, N. Ohuchi, T. Shishido and K. Tsuchiya  
 KEK, Tsukuba, Ibaraki, 305-0801, JAPAN

N. Akaoka, E. Chishiro, T. Hori, H. Kobayashi, M. Nakata, N. Ouchi and M. Yamazaki  
 JAERI, Tokai, Ibaraki, 319-1195, JAPAN

## Abstract

A prototype cryomodule containing two 9-cell superconducting cavities of  $\beta=0.725$  and  $f_0=972$  MHz had been constructed under the collaboration of Japan Atomic Energy Research Institute (JAERI) and High Energy Accelerator Research Organization (KEK) on the development of superconducting LINAC for Accelerator Driven System (ADS). Cool-down tests to 2 K of the cryomodule and high power rf tests with a 972 MHz pulsed klystron have been carried out. Rf power of 350 kW in pulsed operation of 3 msec and 25 Hz was transferred to a nine-cell cavity through an input coupler. Accelerating gradients of 14 MV/m (compared to the specification of 10 MV/m) have been achieved in both cavities. Compensation of Lorentz-force detuning by a piezo tuner was successfully demonstrated.

## INTRODUCTION

Construction of the J-PARC (Japan Proton Accelerator Research Complex) is being carried out aiming at the commissioning in 2007, [1]. The 181 MeV linac section, which consists of normal conducting accelerating structures, will be completed in 2006. A superconducting linac will be added in the second phase of the project, and the 600 MeV  $H^-$  beams will be delivered to the ADS experimental facility. The R&D work on superconducting linac for ADS is being continued in collaboration with JAERI and KEK. A prototype cryomodule with  $\beta=0.725$  (424 MeV) was designed and constructed, [2]. The first cool-down test of the cryomodule was successfully carried out last year, and the cryogenic performance at 2 K and the rf property with low power were reported in [3, 4]. In the successive tests, high power rf system consisting of a 972 MHz pulsed klystron, waveguides, circulators and dummy loads were prepared to study a high gradient operation in a pulsed mode. High field performance of the cavities and observation of mechanical vibration and Lorentz-force detuning in pulsed operation are described in this paper.

## CRYOMODULE

Typical design parameters of the prototype cryomodule are listed in Table 1. The cryomodule includes two 972 MHz nine-cell niobium cavities, which rf parameters are summarised in Table 2. Two cavities named R (right-side) and L (left-side) are made of niobium sheets of 4mm

thick with RRR~250, in order to provide a sufficient stiffness without stiffening rings and to suppress Lorentz-force detuning. The niobium cavity is covered with a titanium jacket of 6 mm thick for filling liquid He of 2 K. Endplates of the He vessel have an optimised shape and thickness so as to obtain a required stiffness of 50 kN/mm.

A cavity tuning system [2] consisting of a stepping motor and a piezo electric transducer is installed outside of the vacuum vessel. Each cavity has a pair of the tuning system, (a piezo is only at one side). Tuning force through two coaxial transmitters drives between both thick endplates of titanium bellows attached at the He vessel. The measured tuning sensitivity and stroke were 200 kHz/mm and 10 mm in the motor tuner, and 100 Hz/ $\mu$ m and 30  $\mu$ m in the piezo tuner, (max.1.0 kV). The elastic constant of the cavity was 1300 N/mm.

Experimental set-up for the high power test is shown in Figure 1. The prototype cryomodule and a valve box surrounded with radiation shields, a waveguide system, transfer tubes and a liquid He-Dewar are shown.

Table 1: Design parameters of the cryomodule.

Pulsed Operation	3.0 msec, 25Hz
Beam Current	30. mA
Temperature	2. K
Eacc	10. MV/m
Qo	$> 1 \times 10^{10}$
Input RF power	300. kW
Qext (Input)	$5 \times 10^5$

Table 2: RF parameters of a 9-cell cavity.

Esp/Eacc	3.07	
Hsp/Eacc	55.4	Oe/MV/m
R/Q	478.	$\Omega$
Geometrical factor	208.	$\Omega$
Cell-to-cell coupling	2.80	%

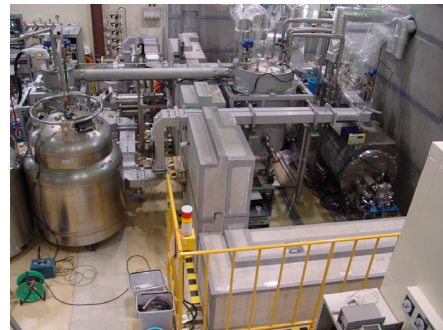


Figure 1: Experimental set-up for the high power test.

<sup>#</sup>eiji.kako@kek.jp

## HIGH FIELD PERFORMANCE

Rf processing of two input couplers was previously carried out at a test stand up to 1.0 MW with 0.6 msec and 50 Hz, [5]. After installation in the cryomodule, the input couplers were baked out at 120 °C for 40 hours. Then, rf processing at room temperature was carried out up to rf input power of 350 kW with 3.0 msec and 25 Hz for about 10 hours in each coupler.

High power test of the cavities was initially carried out at 4.2 K, and the first quench was observed at an accelerating gradient (*E<sub>acc</sub>*) of about 9 MV/m in both cavities. Through a short pulse processing of 0.6 msec, an *E<sub>acc</sub>* of 14 MV/m was finally achieved within 10 hours. Further increase of the *E<sub>acc</sub>* was stopped by heavy x-ray radiation due to field emission. After cool-down to 2.1 K, a stable operation at 12 MV/m exceeding the specification was confirmed in both cavities, as seen in Figure 2. In these tests, the high power rf system had been operated without a feedback control of an amplitude and a phase of the rf input power (*P<sub>inp</sub>*).

Measured *Q<sub>0</sub>* values at 2.1 K and 4.2 K are shown in Figure 3. The drop of the measured *Q<sub>0</sub>* from the black line at 2.1 K means electron loading due to field emission.

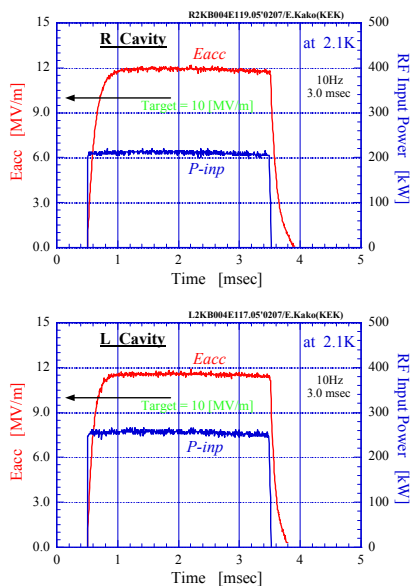


Figure 2: Achievement of target values in both cavities.

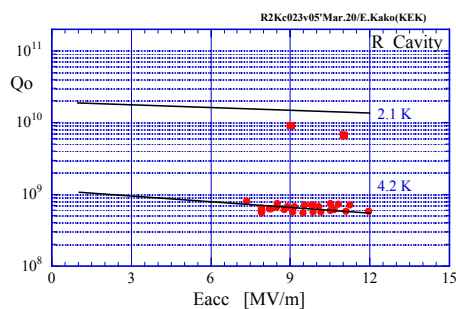


Figure 3: *Q<sub>0</sub>* value measured with flow rate of evaporated He gases in pulsed operation of 25 Hz. Black lines were deduced from a theoretical estimation, *R<sub>res</sub>* = 10 nΩ.

## MECHANICAL VIBRATION

Typical mechanical vibration modes in pulsed operation are summarised in Table 3. The characterised deformation pattern in each mode is shown in Figure 4. Several vibration modes were observed by a measurement using two piezos, of which one is an active oscillator and another is a sensor of deformation. The frequencies measured by a resonant condition with a vibration mode were consistent with the calculation, [6].

Mechanical vibrations caused by repeated rf pulses were detected by a piezo, as shown in Figure 5. Here, the R cavity was operated at 10 MV/m, and there was no rf input power in the L cavity. The frequency of the dominant vibration mode was 160 Hz (150 Hz) in the 10 Hz (25 Hz) operation by FFT analysis of the signal. The frequency is close to the second multi-cell mode, (No.2).

Table 3: Typical mechanical vibration modes.

No.	Mode	Calculation	Measurement
1	multi-cell (I)	86 Hz	81 Hz
2	multi-cell (II)	169 Hz	179 Hz
3	multi-cell (III)	244 Hz	227 Hz
4	tuner mode (I)	294 Hz	304 Hz
41	single-cell (II)	3.91kHz	---

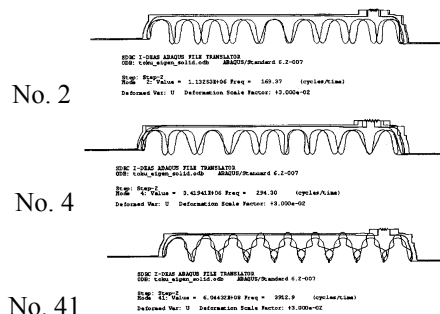


Figure 4: Patterns of mechanical vibration modes, [6].

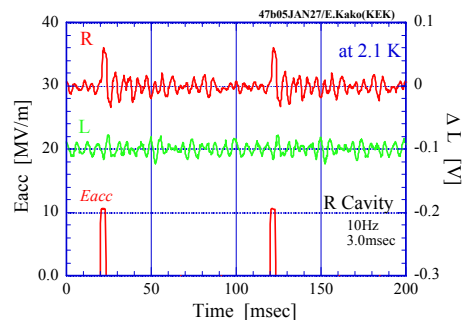


Figure 5: Mechanical vibrations due to rf pulse of 10 Hz.

## LORENTZ-FORCE DETUNING

Rf electromagnetic field in pulsed operation causes a deformation of a 9-cell cavity, so that the resonant frequency shifts with a proportional decrease to *E<sub>acc</sub>*<sup>2</sup>. Figure 6 shows rf pulse signals (*E<sub>acc</sub>*, input power and reflected power) operated at 12 MV/m in the R cavity. The lower figure shows a phase shift between an input and a cavity's monitor signal, and deformation ( $\Delta L$ ) of a

cavity length detected by a piezo tuner. The observed phase shift between the beginning and the end of the pulse was  $-6.5^\circ$ , which is equivalent to the detuning frequency of  $-175$  Hz with the cavity's bandwidth of  $3.0$  kHz. The influence to the Eacc is a slight decrease of only  $0.6\%$ , so that no obvious change is seen in the Eacc signal.

A frequency shift ( $\Delta f$ ) and deformation ( $\Delta L$ ) of a cavity length due to Lorentz-force detuning was systematically investigated, as shown in Figure 7. Calibration of  $\Delta L$  [mV] to the length [ $\mu\text{m}$ ] is under consideration. With their plots to  $E_{acc}^2$ , following linear relations were obtained:  $\Delta f$  [Hz] =  $-1.2 * E_{acc}^2$  [ $\text{MV}^2/\text{m}^2$ ] and  $\Delta L$  [mV] =  $-0.5 * E_{acc}^2$  [ $\text{MV}^2/\text{m}^2$ ]. The obtained coefficient in  $\Delta f$  was nearly equal to the result in a calculated dynamic Lorentz-force detuning ( $-130$  Hz at  $10$  MV/m), [6].

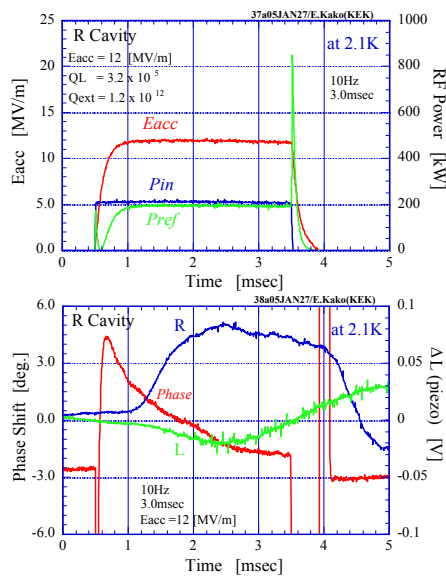


Figure 6: RF pulse signals (upper). Phase shift and deformation of a cavity length (lower).

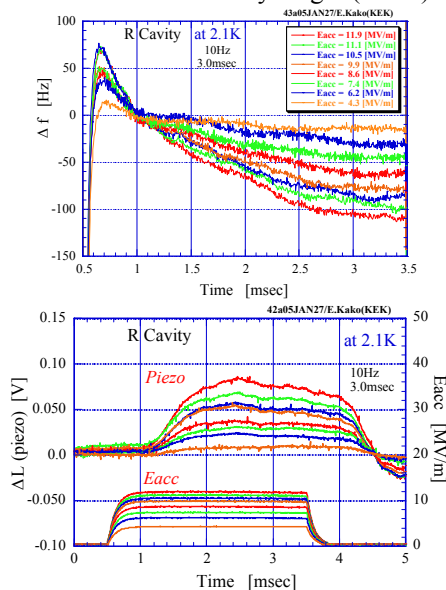


Figure 7: Frequency shift (upper) and deformation of a cavity length (lower) due to Lorentz-force detuning.

## COMPENSATION BY PIEZO TUNER

A piezo tuner with a pulsed voltage can change dynamically a cavity length by a few  $\mu\text{m}$ . As shown in Figure 8, a phase shift due to Lorentz-force detuning at  $10$  MV/m was successfully compensated by a piezo tuner. Mechanical response from a piezo tuner to a cavity is not so fast that there is no change in a phase shift during ramp-up. Moreover, fast components with several kHz like a single-cell mode (see, No.41 in Figure 4) are considered to mainly contribute to the deformation during ramp-up.

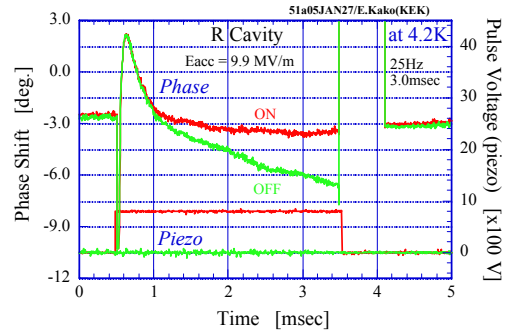


Figure 8: Compensation of Lorentz-force detuning.

## SUMMARY

Accelerating gradients of  $12$  MV/m exceeding the specification had been stably achieved in pulsed operation at  $2.1$  K. Lorentz-force detuning in pulsed operation was systematically investigated, and mechanical vibration modes were measured. Compensation of Lorentz-force detuning by a piezo tuner was successfully demonstrated.

## ACKNOWLEDGEMENTS

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