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DESIGN OF EARTHQUAKE-PROOF STRUCTURE FOR KEK LINEAR ACCELERATOR TANK

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In order to avoid the stress due to thermal expansion and to avoid resonance with an earthquake, the KEK proton linear accelerator tank has as supports a so-called soft-structure.

In this paper we describe the design of the support, i.e. the idea of the structure, the calculation of the mechanical features (the natural frequency, the endurable acceleration etc.) and experimental results with a brief comment on the damping factor.

1 INTRODUCTION

The KEK linac tank is one cavity consisting of six unit tanks and the total length is 15.5 m. Normally the linac is operated at a temperature of (27 ± 1)°C. However, when the machine is shut down and the air conditioning is stopped, the expansion or the contraction for the whole length will amount to several millimeters in a bad case. Further, taking into account frequent earthquakes in Japan, one of the authors (J. Tanaka) proposed to design an earthquake-proof structure for the KEK linac supports.

The degree of the damage due to quakes mainly depends upon the acceleration of the ground and the resonances of the machine with the vibration. It also depends upon other unknown factors as the velocity, the amplitude of the displacement and the duration of the vibration. In the design of the support, we take the former two factors into consideration.

In Japan the earthquake intensity scale is classified into eight ranks and is called J.M.A. (Japan Meteorological Agency) seismic scale. For a tremor of the largest degree, the acceleration of the ground exceeds 400 cm/sec^2 (Ref. 1). It is characterized by the following phenomena: destruction of more than 30% of buildings, landslides, crumbling of mountain sides and changes of geographical features (dislocations, upheavals, subsidences etc.) in a wide area. Therefore we intended to make supports which can endure an acceleration of 0.5 g† in the horizontal plane.

Secondly through Fourier-analysis of microtremors of the ground, the power spectra in the KEK building sites were obtained. It was shown that the natural frequency at the building site ranges from 2.5 Hz to 10 Hz.[2,3]‡ Therefore resonance will be avoided, if the natural frequency of the supports is below 2 Hz.

2 STRUCTURE OF THE SUPPORT

Figure 1 shows the whole view of the KEK linac tank and Figure 2, the side view of the first unit tank. It is around three tons in weight, and is mounted on two supports. The support consists of a steel plate and two preloaded U-shaped steel springs (Figure 3). The former has the role of spring action in the longitudinal direction and the latter, the transverse direction.§

The plate is 1.2 cm in thickness, 78 cm in height and 75 cm in width, having a rectangular hole of 50 cm × 45 cm. The principle to determine the dimensions of the plate is as follows. First, the height is uniquely determined from the beam line

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† g stands for the acceleration of gravity.

‡ The first and the second dominant mode are 5.89 Hz and 3.71 Hz respectively. In the general, the frequency of earthquake in Japan lies between 2 and 20 Hz.

§ We use the term "longitudinal" in the sense of beam direction and "transverse", perpendicular to the beam direction in the horizontal plane.

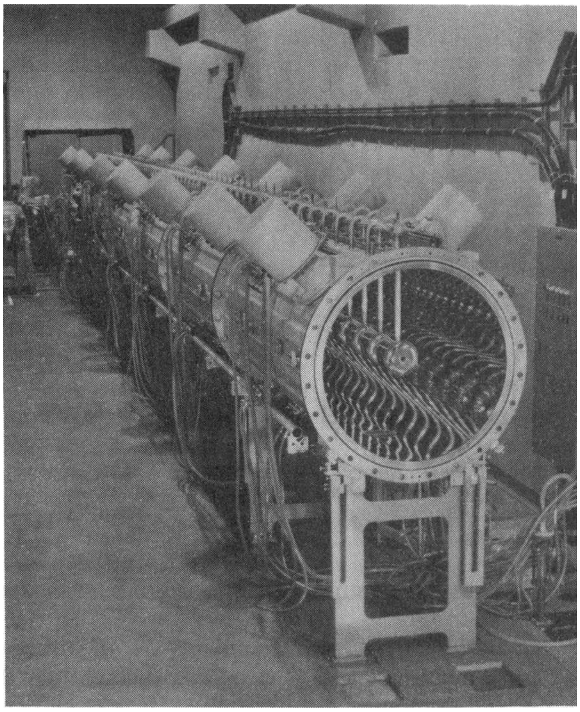

FIGURE 1 Whole view of KEK linac tank.

and the diameter of the cavity. The thickness h and the width b are determined to reduce the natural frequency below 2 Hz, to endure longitudinal acceleration of more than 0.5 g and to make the buckling load larger than the weight of the tank. The structure is shown in Figure 4. The spring plate is indicated by ①. The height of the cavity can be finely adjusted with four screws ②.†

The U-shaped spring ③ is 3 cm in thickness, 3.2 cm in width and 47.4 cm in length. It is also designed to have a natural frequency of 2 Hz. In order to reduce the frictional force an assembly of needle bearings ④ and a guiding plate ⑩ is inserted between the legs of the tank ⑤ and the adjusting screws ②. A pair of mating blocks ⑥ having a groove in the transverse direction is attached to the legs and the upper end of the spring plate. Each mating block has a pin hole ⑦, to which each end of the U-shaped spring is fixed. So as not to fail in exact repositioning, the U-shaped spring is pretensioned to 28 kg/mm^2 by the

† The method to set up the unit-tanks (and the drift tubes) on the beam-line will be reported elsewhere. We merely mention here that the tanks are well aligned if the screws can be rotated with the effective up and down movement of ± 5 mm.

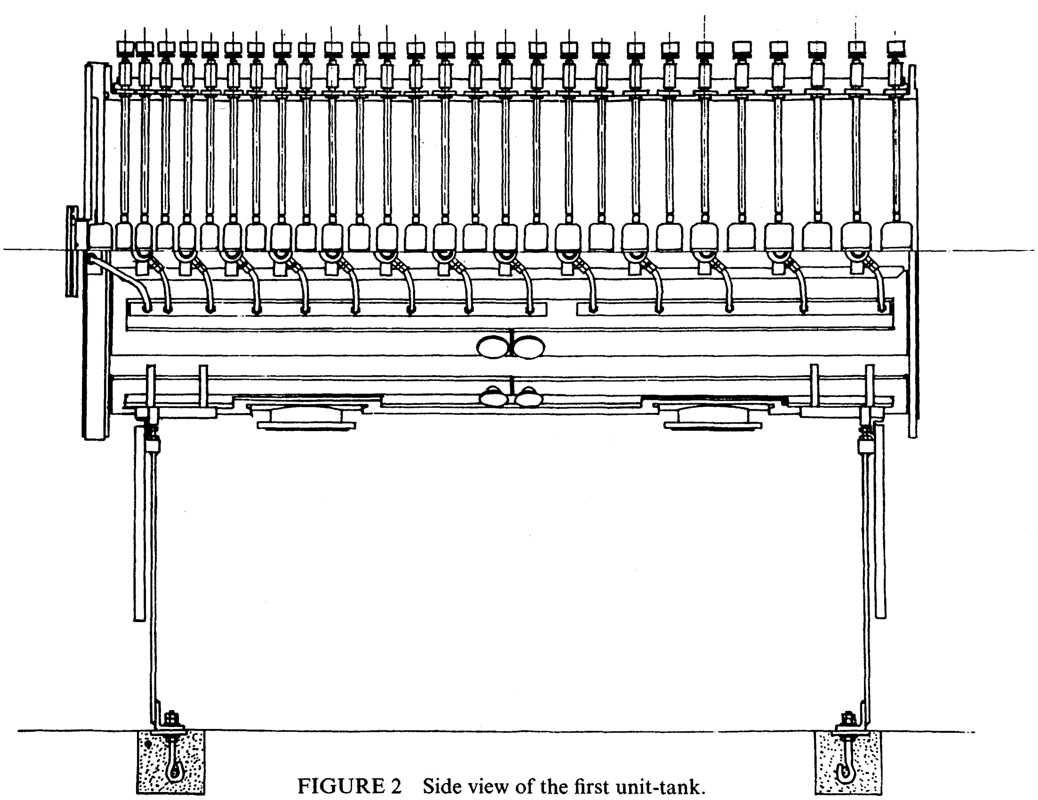

FIGURE 2 Side view of the first unit-tank.

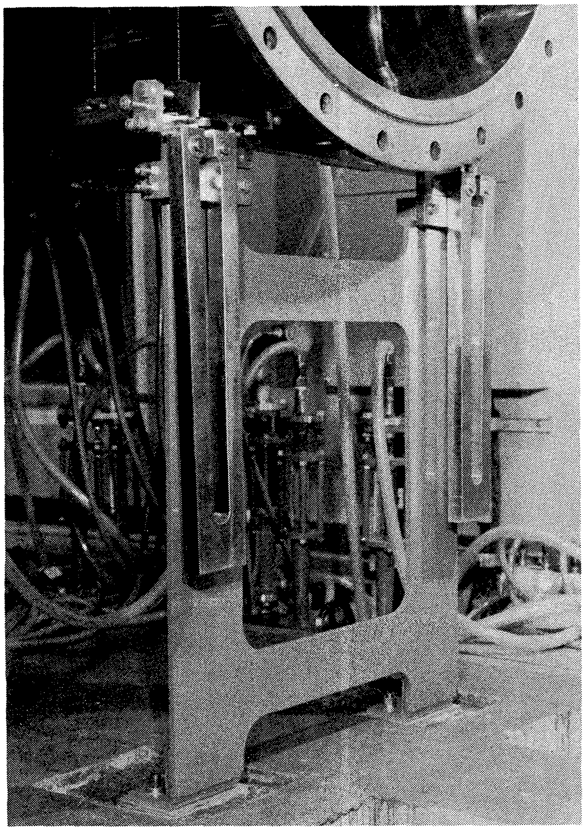

FIGURE 3 Structure of the Support I.

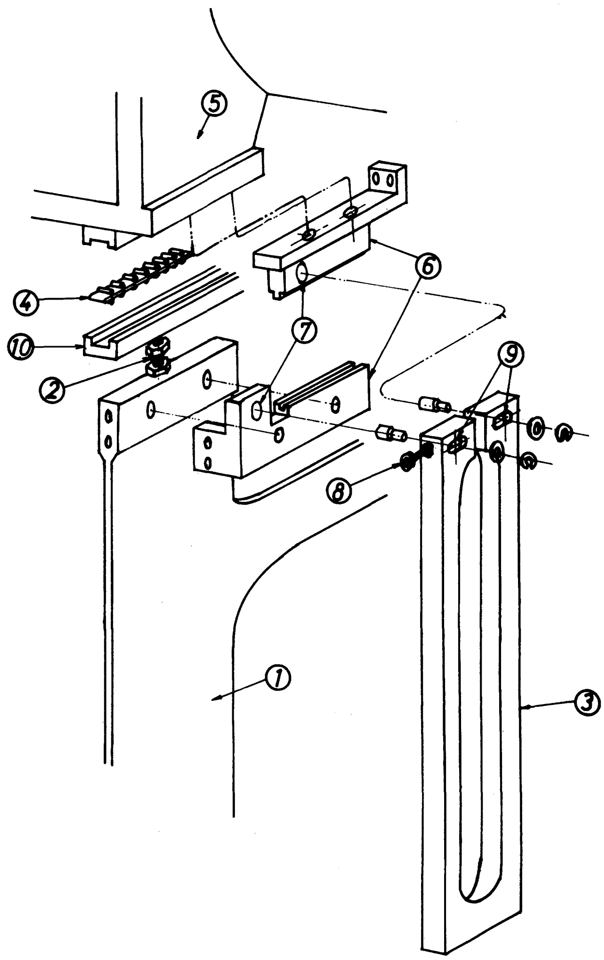

FIGURE 4 Structure of the Support II.

screws ⑧. This strength corresponds to a transverse acceleration of 0.2 *g*. The spring has only leftward restoring force in the case of Figure 4; spring action occurs for a stretching force which exceeds the preset value, but does not for any compressive force owing to the clearance of a track-shaped hole ⑨. Therefore it can be said that for the transverse direction, the support is a rigid structure below the acceleration of 0.2 *g*, but becomes a soft structure above that value (Figure 5).

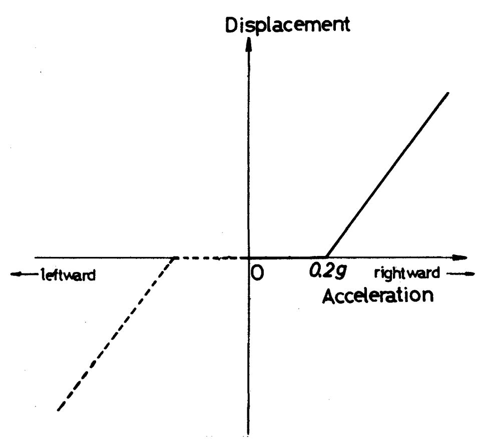

FIGURE 5 Acceleration-displacement diagram for the transverse movement.

3 PROPERTIES IN THE LONGITUDINAL DIRECTION

As two guiding blocks are bolted on the upper end of the support and two anchor bolts are buried at the lower end of the support, we can take the boundary condition as follows. The upper end of the plate is free for displacement but restricted in rotation, meanwhile the lower end is fixed both for displacement and rotation. Let the *x*-axis be

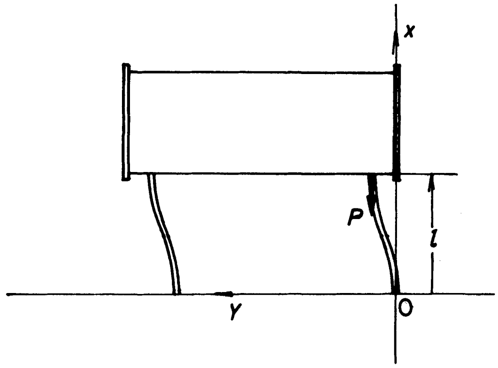

FIGURE 6 Coordinate of a plate spring.

vertical and the Y-axis along the longitudinal direction (Figure 6). Then

$$Y = 0, \quad \frac{\partial Y}{\partial x} = 0 \quad \text{at } x = 0 \tag{1a}$$

$$F_s = 0, \quad \frac{\partial Y}{\partial x} = 0 \quad \text{at } x = l \tag{1b}$$

in which the displacement Y is a function of x and t, and F_s means the shearing force. If we denote Young's modulus by E and the geometrical moment of inertia by I, then the bending moment M can be expressed as follows:

$$M = EI\frac{\partial^2 Y}{\partial x^2} \tag{2}$$

F_s is given by

$$F_s = EI\frac{\partial^3 Y}{\partial x^3} + P\frac{\partial Y}{\partial x}, \tag{3}$$

where P is the weight of the tank.

3.1 *Natural Frequency*

We consider the restoring force due to the deflection of the elastic plate. Let the mass on the upper end be m, and assume the mass of the plate be negligible. The bending moment exerting at any point (x, Y) is due to the load P and the force of inertia F (Figure 7), being expressed as follows.

$$M = F\left(\frac{l}{2} - x\right) + P\left(\frac{Y_l}{2} - Y\right), \tag{4}$$

where

$$F = -m\left(\frac{\partial^2 Y}{\partial t^2}\right)_{x=l}. \tag{5}$$

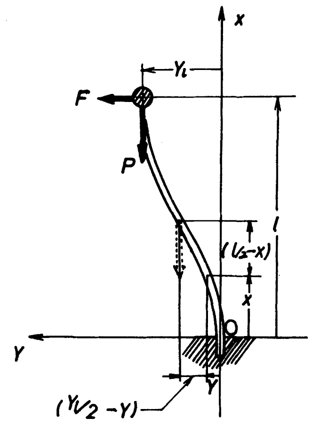

FIGURE 7 Flexible pillar model.

Then, Eq. (2) becomes

$$EI\frac{\partial^2 Y}{\partial x^2} + m\left(\frac{l}{2} - x\right)\left(\frac{\partial^2 Y}{\partial t^2}\right)_{x=l} - P\left(\frac{Y_l}{2} - Y\right) = 0. \tag{6}$$

As the time variation is independent of the position, Y can be written as follows.

$$Y = y(x)\cos(\omega t). \tag{7}$$

From Eqs. (6) and (7), we get

$$EI\frac{\partial^2 y}{\partial x^2} + Py = \left\{m\omega^2\left(\frac{l}{2} - x\right) + \frac{P}{2}\right\}Y_l, \tag{8}$$

the general solution of which is given

$$y = C_1\cos\left(\sqrt{\frac{P}{EI}}\,x\right) + C_2\sin\left(\sqrt{\frac{P}{EI}}\,x\right) + \left\{\frac{m\omega^2}{P}\left(\frac{l}{2} - x\right) + \frac{1}{2}\right\}Y_l. \tag{9}$$

Using the boundary condition (1), we can determine C_1 and C_2 to get

$$y = -\frac{Y_l}{2}\left(\frac{m\omega^2}{P} + 1\right)\cos\left(\sqrt{\frac{P}{EI}}\,x\right) + \sqrt{\frac{EI}{P}}\cdot\frac{m\omega^2}{P}\,Y_l\sin\left(\sqrt{\frac{P}{EI}}\,x\right) + \left\{\frac{m\omega^2}{P}\left(\frac{l}{2} - x\right) + \frac{1}{2}\right\}Y_l. \tag{10}$$

Putting $y = y_l/2$ at $x = l/2$, we get the natural frequency f.

$$f = \frac{1}{2\pi}\sqrt{\frac{P}{ml}}\,\frac{1}{\sqrt{\frac{2}{l}\sqrt{\frac{EI}{P}}\tan\left(\sqrt{\frac{P}{EI}}\cdot\frac{l}{2}\right) - 1}}. \quad (11)$$

Taking l† $= 78$ cm, $E = 2.09 \times 10^6$ kg cm^{-2}, $P = 1.5 \times 10^3$ kg and $I = 4.32$ cm^4‡, we get

$$f = 1.88 \text{ Hz}.$$

If the denominator in Eq. (11) becomes infinite, the natural frequency f goes to zero. The load P_c at which this condition is satisfied is called the Euler's critical buckling load; the lowest mode of which is given by

$$P_c = EI\left(\frac{\pi}{l}\right)^2. \quad (13)$$

With the same values as those in the preceding section, P_c is evaluated to be 1.47×10^4 kg. Therefore the safety factor becomes 9.8.

3.2 *Longitudinal Critical Force*

Due to the vibration of the ground, a forced oscillation is induced to the tank. In this section, however, we suppose a static model. At the initial time when the ground moves in one direction suddenly, the tank is left at the original position due to inertia. We assume that the period of the vibration is long enough and do not consider the subsequent reverse movement of the ground. If the acceleration of the ground is very large, the bending stress at some cross section of the support exceeds the yield strength of the material used. We call the force corresponding to this acceleration the critical force. The actual acceleration which the support can endure will be much larger than that calculated here, because the tensile strength is about two times larger than the yield strength.

† Owing to the reinforcement and the installation of the height-adjusting mechanism, l does not coincide with the real height of the support.

‡ The geometrical moment of inertia is given by

$$I = \frac{bh^3}{12}. \quad (12)$$

The thickness h of the plate is 1.2 cm. But the width is 75 cm having a rectangular hole of 45 cm (in width) × 50 cm (in height). So we tentatively take $b = 30$ cm.

The maximum bending stress σ_{max} at an arbitrary cross section of a beam is given as follows.

$$\sigma_{max} = \frac{M}{I}e = \frac{M}{Z}, \quad (14)$$

where e is the maximum distance from the neutral axis and Z, the modulus of section. It is given by

$$Z = \frac{I}{e} = \frac{bh^3/12}{h/2} = \frac{bh^2}{6}. \quad (15)$$

The bending moment M takes the largest value at $x = 0$ and $x = l$, neglecting the second term in Eq. (4). Then Eq. (14) becomes

$$\sigma_{max} = \frac{3Fl}{bh^2}. \quad (16)$$

Using the minimum yield strength† of SS41P, $\sigma_{max} = 25$ kg/mm^2, we get

$$F = \frac{\sigma_{max}\cdot bh^2}{3l} = 4.62 \times 10^2 \text{ kg},$$

which corresponds to a horizontal acceleration of 0.31 g.‡ It can easily be shown that the deflection is 2.0 cm for this acceleration.

4 PROPERTIES IN THE TRANSVERSE DIRECTION

4.1 *Natural Frequency*

We use a simple pendulum model for the calculation of natural frequency.

$$f = \frac{1}{2\pi}\sqrt{\frac{k}{m}}. \quad (17)$$

Due to the sequence of two cantilevers in the U-type blocks, the spring constant k is given as follows§ (Figure 8):

$$k = \frac{3EI'}{l'^3} \times \frac{1}{2} = \frac{Eb'h'^3}{8l'^3}. \quad (18)$$

† SS41P is rolled steel plate for general structure (JIS G3101). The yield strength is more than 25 kg/mm^2 and the tensile strength, 41 ~ 51 kg/mm^2.

‡ If we use the tensile strength of 41 kg/mm^2 for σ_{max}, the endurable horizontal acceleration becomes 0.51 g.

§ For a cantilever the boundary condition is given as follows.

$$y = 0, \quad \frac{dy}{dx} = 0 \quad \text{at } x = 0 \quad (19a)$$

$$F_s = 0, \quad M = 0 \quad \text{at } x = l' \quad (19b)$$

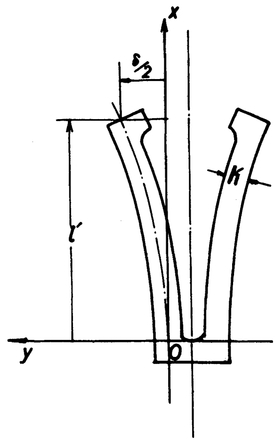

FIGURE 8 Coordinate of a U-shaped spring.

When a concentrated load F' is exerted on the one end of a cantilever, the cross section of which is rectangular, the maximum bending stress σ'_{max} is given by Eq. (20).

$$\sigma'_{max} = \frac{6F'l'}{b'h'^2}. \qquad (20)$$

Corresponding to the pretensioned force $F' = 0.2$ mg, we decided to make $\sigma'_{max} = 28$ kg/mm^2, which is about half of the yield strength of S45C.† Substituting $f = 2$ Hz into Eqs. (17), (18) and (20), we get relations between b', l' and h'. Using $b' = 3$ cm for the thickness of the spring, we get $h' = 3.2$ cm and $l' = 47.4$ cm. Therefore the deflection δ of the spring, which we give, corresponding to the initial pretension, is given by

$$\delta = \frac{F'}{k} = 6.25 \text{ mm}.$$

4.2 *Transverse Critical Force*

Just as in Sec. 3.3, the maximum transverse acceleration can be obtained by substituting the yield strength or the tensile strength for σ'_{max} in Eq. (20). From this we get 0.36 g and 0.5 g respectively.

5 EXPERIMENTAL RESULTS

The natural frequency in the longitudinal direction was measured for the first unit tank. A permanent magnet was attached to the end flange, after the completed unit tank had been placed in the correct location. The oscillations of the magnet against a Hall probe, which was fixed to the floor, generated the signal voltage (Figure 9). The measured natural frequency and the damping factor were 1.72 Hz and 1.46 sec respectively. The former is 9.3% smaller than that calculated in Sec. 3.1, which coincides rather well in spite of the rough estimation.

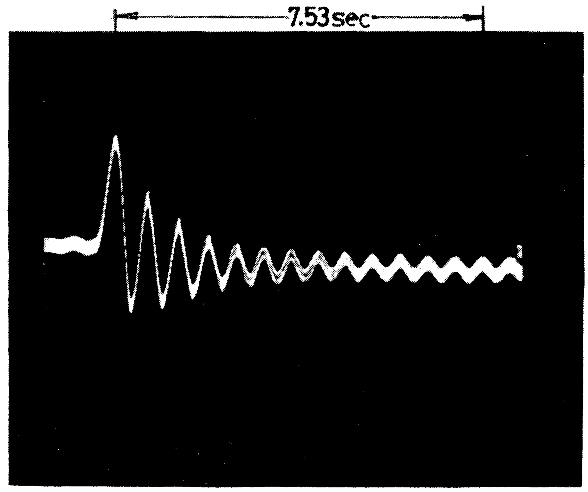

FIGURE 9 Oscillation of the first unit-tank.

As we have lost the opportunity to get any experimental result about the transverse oscillation, since the alignment of the whole tanks and drift tubes has been completed, we are going to measure the frequency by monitoring real earthquakes.

In the design of earthquake-proof structure, it is also necessary to make fast damping. We consider that there is no problem for the transverse structure because of the nonlinearity of the righting force. For the longitudinal structure there is no intended device for damping. We hope that the installation of twelve sputter-ion pumps, two rf feeders and beam transport systems will serve as dampers to some extent. However, we are also investigating the possibility of an oil damper.

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† S45C is a carbon steel for machine structure use (JIS G4051). The yield strength and the tensile strength are more than 50 kg/mm^2 and 70 kg/mm^2 respectively.

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