THE EFFECT OF ACCELERATOR PARAMETERS ON MECHANICAL TUNING OF rf CAVITIES*

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Summary

The rf system of a proton synchrotron requires a frequency-modulated rf voltage to accelerate the particles. This paper discusses a unique method for frequency modulation of rf cavities by means of a "Loud Speaker" type of mechanical rf tuning system of the type originated by W. Schnell of CERN.[6]

A typical mechanically tuned rf system for a medium-energy high-repetition-rate particle accelerator is used to illustrate (a) the optimization of the moving portion of the tuner; (b) the control system and the response limits on the servo loop; (c) the mechanical response of the moving part and its effect on tuning accuracy.

The cavity parameters are shown on Table I. The effect on the tuning parameter of changing the accelerator parameter is presented. A brief comparison between mechanical tuning and conventional ferrite tuning is shown.

1. Characteristics of the Loud Speaker Mechanical Tuner

The cavity is tuned to the desired frequency by changing the width of the accelerating voltage gap by means of a moving plunger. The plunger must be large enough to enclose the ion beam and its vacuum tank. The forces required to move the plunger are supplied by current in a coil wound around one end of the plunger, which is in a magnetic field. The principle of operation is exactly the same as a loud speaker. (See Fig. 1.)

The magnetic field is supplied by a dc magnet that is oriented so that the field passes radially across the plunger and the current-carrying coil. The force acts longitudinally along the plunger. A tuning plate is located at the other end of the plunger, which is opposite a stationary plate mounted on the reentrant portion of the cavity. The motion of the cavity plunger is governed by the equations[2]

$$F = ma = B\ell i$$

and $$m = m_p + m_c,$$

where
F = instantaneous tuning force,
a = instantaneous plunger acceleration,
m_p = mass of the plunger,
m_c = mass of the tuning coil,
m = total moving mass,
B = dc magnetic induction,
ℓ = length of wire in the tuning coil,
i = current flow in the coil.

From the basic equation of motion the instantaneous driving current can be calculated:

$$i = \frac{ma}{B\ell}.$$

The instantaneous power consumption is

$$P = i^2R,$$

where R = coil resistance.

The heat transferred from the tuning coil is a function of i^2R loss over the acceleration cycle,

$$Q_c = \left(\int_0^t P dt\right)/t.$$

The instantaneous voltage required to drive the coil is

$$E = iR + i\frac{dL}{dt} + L\frac{di}{dt},$$

where $$i\frac{dL}{dt} = B\ell v.$$

The instantaneous change in stored energy in the electromechanical system is

$$P_s = i^2\frac{dL}{dt} + i L\frac{di}{dt}$$
$$= mav + i L\frac{di}{dt},$$

where

v = instantaneous velocity of the plunger,
L = inductance of the tuning coil,
E = instantaneous voltage,
P = instanteneous power consumption,
P_s = instantaneous stored energy change,
Q_c = heat to be transferred from the plunger,
T = time for one acceleration cycle.

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An optimization of power loss is presented in references 2 and 3. A summary of the tuning-coil parameters that resulted from this optimization is shown as follows:[2]
(a) The moving mass should be minimized.
(b) The mass of the tuning coil should equal the mass of the plunger.
(c) The product of resistivity and density for the wire used in the tuning coil should be a minimum (copper wire is not the best wire to use).
(d) The dc magnetic field should be high. Heat dissipation and inductive power decrease as the field increases.[3] The exact value of the field can be determined by optimizing the magnet and power costs.

The number of rf cavities required in a particle accelerator is a function of the maximum allowable voltage gradient across the gap. In general, the greater the minimum gap width, the fewer the number of required rf cavities[3] (note that there are other factors which may limit the cavity voltage).

2. The Effect of Plunger Design on the rf Cavity Control System

The control system which tunes the rf cavity compares the frequency of the untuned cavity with the required cavity frequency as measured from the magnet and beam probes. The ability of the cavity to tune is dependent on the response of the control loop. The plunger acts as an electromechanical transducer which transmits an electrical signal from the tuning coil to the tuning plate.

The response of the control system is limited by the speed of sound in the plunger. The response frequency for the control system can be no higher than the lowest excited mechanical vibration that affects the longitudinal motion of the plunger. Assuming the plunger is a cylinder, there are two modes of vibration which will affect the cavity tuning: the longitudinal vibration and radial vibration.[1]

The lowest mode of each vibration is given below.

Longitudinal

$$fm = \frac{a}{2\ell},$$

Radial

$$fm = \frac{1}{2\pi}\frac{a}{r},$$

where

$$a = \left|\frac{E}{\rho}\right|^{1/2},$$

a = sound speed,
E = Young's modulus,
ρ = density of the plunger,
r = radius of the plunger,
fm = frequency of vibration,
ℓ = length of the plunger.

The radial mode of vibration is coupled directly with the longitudinal mode by Poisson's ratio,

$$Q = \frac{f}{2\Delta f} \approx \frac{\omega_c f}{2\dot{f}},$$

where $\omega_c = 2\pi fm$

and Q = ratio of circulating energy to energy loss,
f = rf frequency,
Δf = band width,
$\dot{f}$ = rate change of f.

The servo-loop response time can be reduced by making the plunger as small as possible and by making the plunger from a material with a high sound speed. The radial dimensions of the plunger are limited by the aperture of the ion beam, hence, the radial mode of vibration is the limiting one. Beryllium has the highest sound speed (12 900 m/sec) and the lowest Poisson ratio (0.02) of any material. Beryllium, however, is difficult to handle and is toxic. Aluminum has excellent properties for this purpose, though, provided the limitation by the sound speed (5000 m/sec) is not too severe.

A tuning plunger shown in Fig. 2 for the 200-Mc rf cavity shown in Fig. 1 would be made of aluminum or beryllium not more than 0.5 mm thick. The slots in the plunger reduce eddy currents generated by the plunger's motion in the dc magnetic field. The tuning coil would be made of aluminum wire (minimum $R_e\rho$), and would be about 2 cm long.

Table I. The physical characteristics for a mechanical tuner for given accelerator parameter

Parameters of the proton accelerator	
Repetition rate	15 cps
Sinusoidal magnetic field	
Injection energy	200 MeV (β = 0.566)
Ejection energy	10 BeV (β = 0.996)
Range of rf frequency	113 to 199 Mc
Frequency swing	0.761
Momentum spread of the injected beam	1.5×10^{-3}
Characteristics of the cavity (see Fig. 1)	
Characteristics of the tuner	
dc Magnetic field	10 kilogauss
Plunger dimensions	See Fig. 2
Mass of the plunger and tuning coil	100 g
Length of wire in tuning coil	1050 cm
Resistance of the coil	0.268 ohm
Displacement, Velocity, and Acceleration	
Maximum displacement	1.675 cm
Minimum displacement	0.25 cm
Maximum velocity	144 cm/sec
Maximum acceleration	1.56×10^5 cm/sec^2
Maximum plunger force	156 newtons = 35 lb

Voltage, Current, and Tuning Power

Maximum current	15.7 A
Maximum voltage	29.2 V
Peak power i^2R	65.7 W
Peak back-emf power	225.0 W
Peak inductive power	72.5 W
Peak amplifier power required	363.2 W
Average heat dissipation	≈ 2 W

rf Voltage and the Number of Cavities Required

Peak accelerating voltage	1.2 MeV/turn
Peak voltage gradient across gap	28.8 kV/cm
Number of required cavities	64

3. The Effect of Accelerator Parameter on Mechanical Tuning

The accelerator parameters that affect mechanical tuning are: accelerator repetition rate, the cavity rf frequency, the accelerator injection energy and ejection energy, and the magnetic field cycle. These parameters affect tuning power, heat dissipation, tuner forces, and the number of rf cavities required.

The most important single accelerator parameter that affects the rf tuning is the machine repetition rate. If the repetition rate given in Table I is doubled, the velocity of the plunger is doubled and the acceleration is increased four times. The heat dissipation is increased 16 times, the inductive power 32 times, and the back emf power 8 times. The ability for the system to tune is reduced to half and the number of rf cavities required is doubled.

If the rf frequency of the machine is reduced, the cavities must be larger to accommodate the changes in wave length of the rf. The plunger displacement is increased. As a result, the velocity, acceleration, power consumption, and heat generation are increased. The number of cavities can be reduced. The change in tuning parameters depends on the geometry of the cavity and its tuning elements.

The machine injection energy affects the tuning range (rf frequency swing) of the machine. A decreased tuning range results in lower plunger velocity and acceleration, with a resulting reduction in current and voltage required. The tuning ability of the cavity increases as the rf frequency swing decreases.

The ejection energy affects the velocity and acceleration of the plunger during the early part of the cycle. Hence it affects both the power required to tune the cavity and its ability to tune.

The accelerator magnetic field cycle has a small effect on tuning. If the magnetic field rise is reduced early in the cycle, then the maximum rate of change of rf frequency is reduced. As a result the cavity tuning characteristics are improved.

The cavity described in Table I was chosen to demonstrate the application of mechanical tuning for medium-energy high-repetition-rate accelerators. This application of mechanical tuning is near the upper limit of its feasibility. The following practical limits may be set for the feasibility of mechanical tuning for medium-energy machines:
(a) The repetition rate should not exceed 30 cps.
(b) The frequency swing should not be greater than 1.
(c) The rf frequency at its maximum should be 100 Mc or greater.
(d) The tuning number, Γ should not exceed 2:

$$\Gamma = \frac{\Xi f_r E_{ei}}{\alpha f_{max}} \leq 2,$$

where

Ξ = rf frequency swing = $\dfrac{f_{max} - f_{min}}{f_{min}}$,

f_r = repetition rate (cps),

E_{ei} = ejection energy ratio = E_K/E_0,

E_K = kinetic energy of the particles,

E_0 = rest mass energy,

f_{max} = maximum rf frequency (Mc),

f_{min} = minimum rf frequency,

Γ = the tuning number,

α = sound speed ratio = $\dfrac{a_{plunger}}{a_{aluminum}}$

Mechanical tuning offers the following advantages over conventional ferrite-tuned, medium-energy high-repetition-rate machines:
(a) The power required to tune the cavity is negligible compared with the bias power required for ferrite tuning;
(b) one low-cost servo control can tune more than one cavity;
(c) there is a probable increase in the effective cavity Q;
(d) the rf power is lost where cooling is relatively easy.

However, the problems associated with the mechanical tuning must also be considered:
(a) More rf cavities are required.
(b) Cavity construction cost is likely to be higher than for ferrite-tuned cavities.[5]
(c) Mechanically tuned cavities are likely to be less reliable than ferrite-tuned cavities.
(d) Clean fast extraction is not possible because of the high rf frequency required. As a result, much higher radiation levels at fast extraction septums can be expected.

Loud speaker mechanical tuning of rf cavities show promise on machines with low rf frequency swing ($\Xi \leq 0.1$) and low repetition rates ($f_r \leq 2$ cps). I have investigated two rotary mechanical tuning systems.[4] These systems, however, must be ferrite-trimmed to tune within the required accuracy.[5] I do not share the optimism shown by others for mechanical tuning on high-repetition-rate medium-energy accelerators.

References

1. Michael A. Green, Vibration in the Mechanical Tuning Plunger, Lawrence Radiation Laboratory Report UCID-2450.

2. Michael A. Green, The Electrical and Mechanical Properties of the Mechanical Tuning System, Lawrence Radiation Laboratory Report UCID-2451.

3. Michael A. Green, A Mechanical Tuning System for a Cavity to be Tuned from 50 Mc to 100 Mc, Lawrence Radiation Laboratory Report UCID-2452.

4. Michael A. Green, A Rotary Capacitive Tuning System for a 50-Mc to 100-Mc rf cavity, Lawrence Radiation Laboratory Report UCID-2453.

5. Michael A. Green, The Ferrite-Trimmed Mechanically Tuned rf Cavity, Lawrence Radiation Laboratory Report UCID-2454.

6. W. Schnell, On the High Power Radio-Frequency System for a Booster for a 300-BeV Proton Synchrotron, LRL AR/INT SG/63-2, January 11, 1963.

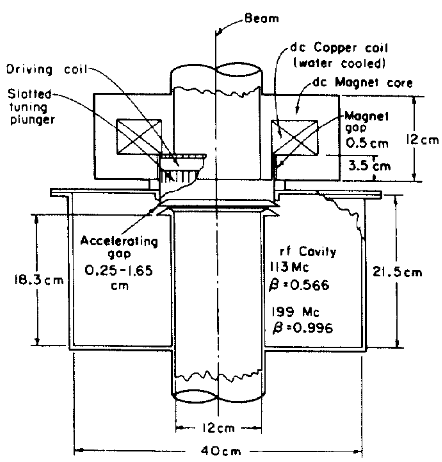

Fig. 1. The RF cavity described in Table I.

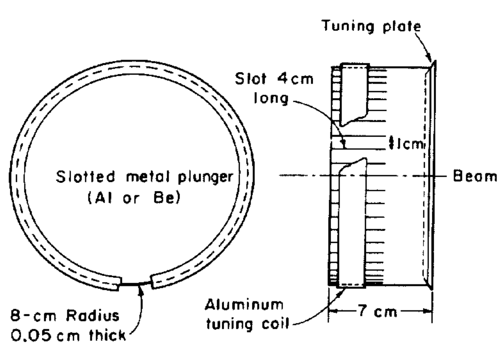

Fig. 2. The mechanical tuning plunger.

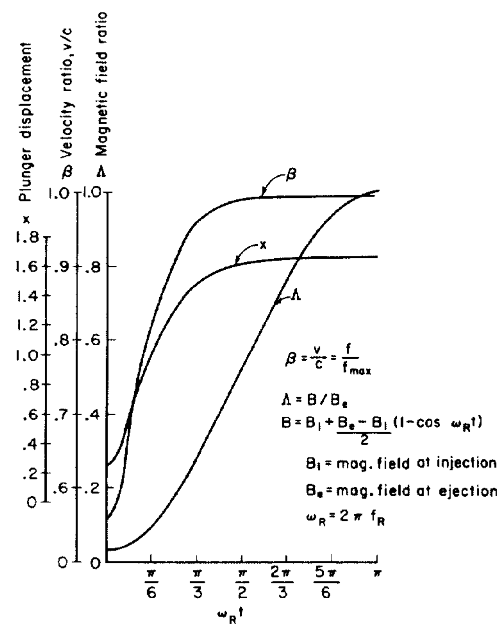

Fig. 3. The magnetic field ratio, velocity ratio, and plunger displacement during the accelerating portions of the cycle described in Table I.