Accelerating System for the Cornell 10 GeV Electron Synchrotron

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The above paper was presented at the conference, but was not available for publication.

DISCUSSION (condensed and reworded)

M.C. Crowley-Milling (Daresbury): How would you proceed to increase your power capability if eventually this were required by an increase in top energy to 15 GeV or more?

Tigner: By using larger klystrons capable of 7MW; these are designed, but not available off the shelf.

RESULTS ON HIGH-POWER MODELS OF MECHANICALLY TUNED CAVITIES FOR FAST-CYCLING BOOSTER SYNCHROTRONS

by

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1. Introduction

Several years ago r.f. accelerating cavities tuned by a mechanical servo system have been proposed for fast cycling booster-synchrotrons[1,2). Since then, experimental development work with this scheme has been pursued and has led to the construction and testing of several stages of full-size high-power models. The results obtained with the latest model are reported here.

2. Description of the model

The design of the cavity is basically the same as described in[1,2). A re-entrant cavity is equipped with a capacitive tuning piston, situated opposite the high-voltage end of the cavity. The piston carries a drive-coil that is exposed to a radial d.c. magnetic field, i.e. the drive system is the same as that of an ordinary loud-speaker. The piston is made of aluminium alloy and has a total mass of 200 g. It floats on a system of 8 air-bearings, having a pressure drop of about 3 atm. The air leaving these bearings is further employed to pressurize the cavity to about 4.5 atm. gauge. The gap from the end-cone of the piston to the high-voltage terminal of the cavity varies from 1 to 11 mm. The corresponding frequency variation is 100 to 180 MHz corresponding to 200 MeV injection energy. The r.f. current is carried to the outer conductor of the resonator via an 0.3 mm gap between the cylindrical wall of the piston and the surrounding structure. A tubular beryllium-oxide vacuum-seal traverses the accelerating gap. The entire cavity is shown in Fig. 1.

The anode of the final amplifier tube is coupled to the cavity via a short length (about 0.5 m) of rigid coaxial line. This line provides a frequency-dependent voltage transformation such that the r.f. voltage at the anode remains approximately constant during most of the accelerating cycle while the gap-voltage follows the required programme. This allows one to obtain a good efficiency of the final amplifier without the use of an anode modulator. The coupling line also leads to a physical separation of amplifier and cavity which is very convenient for maintenance and repair. Only the final amplifier tube and its enclosure have to be located near the cavity. The driver amplifiers and all electronic equipment pertaining to the tuning system can be located outside the accelerator tunnel.

The final amplifier of the latest model is equipped with an air-cooled UHF-tetrode (Siemens RS 1032 C) of 12 kW maximum permissible anode dissipation. However, the average anode dissipation in our circuit is only about 6 kW. The peak r.f. power delivered by the tube is about 8 kW. The peak drive-power required is 250 W on a matched 50 ohm line. This is delivered by a six-stage band-pass type distributed amplifier. Both the driver amplifier and the final amplifier's input are wide-band fixed-tuned.

The drive-coil current is controlled by a servo-amplifier taking its information from a measurement of phase between the input and output of the final r.f. amplifier. The cut-off frequency of this servo-system is limited by mechanical resonances in the piston end-cone. Unity loop-gain still occurs at about 3 kHz as in our earlier low-power models. However, there are now two refinements:

Firstly, the main servo-system is assisted by a pre-regulation system of about 5% accuracy. Two alternative kinds of pre-regulation are employed:

i) an 80 - point adjustable function generator,

ii) a 50 ms LC delay-line that samples the analogue-voltage at a suitable point of the servo-system, stores all information for one period of the 20 Hz repetition-rate and feeds it back into the system during the next acceleration cycle.

The latter system, which takes advantage of the repetitive character of the machine cycle, has the advantage of great simplicity and reliability but it needs starting by means of the first system.

Secondly, the quality-factor, Q, of the cavity, which is controlled by artificial damping, is made frequency dependent in such a way that it is lowest at injection which is near the point where the rate of change of frequency, and hence the dynamic tuning error, are largest.

3. Results

All our models have been made to track the frequency programme corresponding to an 8 GeV proton-synchrotron with 200 MeV injection-energy and a 20 Hz biased sinusoidal magnet cycle. In the latest model, the Q-factor can be made to vary from 1700 at injection to 5500 at top frequency, the latter figure being the natural Q of the cavity, including the losses in the beryllia vacuum seal. These Q-factors, and the corresponding values of shunt impedance, are an order of magnitude higher than the conservative predictions of Ref. 1,2). This is mainly due to the pre-regulation system described above.

The peak gap-voltage obtained is 30 kV at the maximum frequency and 10 kV at the injection point. Between these two points the voltage has been made to follow a curve that satisfies approximately the following conditions: After injection the voltage rise is such as to yield a constant bucket-area of 10^{-2} in units of r.f. phase and $(\Delta p/m_o c)$ where Δp is the deviation of particle momentum from the synchronous value and $m_o c^2$ is the rest energy. This bucket area would be required for adiabatic trapping of an unbunched linac beam of $\pm$ 250 kV energy spread, which is considered generous. If the linac beam were bunched at the booster injection frequency and phase an even greater energy spread could be tolerated. Later in the acceleration cycle when the voltage corresponding to constant bucket area would lead to synchronous phase angles in excess of 45° the voltage rise is made to follow a sinusoid, so as to keep approximately constant phase-angle up to the point of maximum energy gain per turn. After this point, the voltage is kept constant.

In applying this voltage programme we have, occasionally, had sparking difficulties, especially across the 0.3 mm gap at the side-wall of the piston. However, we have always been able to trace these incidents to mechanical damage of the piston due to mishandling during manufacture and experimentation or - more often - to gross impurities in the supply of compressed air. A closed-circuit compressor using pure nitrogen is being installed at present.

Steady state beam-loading corresponding to a tightly bunched beam of 200 mA average current at $\beta = 1$ has been approximated by a separate load resistor, coupling loop and frequency-dependent transformation network. The real beam-power corresponding to this is included in the power figures given in Section 2. However, neither transient loading, nor possible interactions at higher harmonics have, so far, been studied experimentally.

4. Application to a booster synchrotron

A booster ring of 60 m average radius could be equipped with 36 cavities. Then, even with 6 cavities out of order one could keep the synchronous phase below 45° and the bucket area above 10^{-2} (in the units given above). In practice one is likely to run with a smaller bucket area so that the safety margin is even larger. In the design[3] the cavities are supposed to be located in 9 different straight sections. The final frequency chosen is 167 MHz, which is somewhat smaller than in our models but not difficult to obtain.

5. Life test

None of our complete models has as yet been operated over long periods of time. However, a complete mechanical tuner, consisting of piston, drive system and air-bearing, is being subjected to a continuous life test. For this test the piston is made to follow a 50 Hz sinusoidal oscillation of somewhat increased stroke, so that the peak values of speed and force are about the same as in the real case.

This set-up is running almost continuously since the beginning of 1965. Up to now, the actual accumulated running time is 10,000 h, corresponding to 25,000 h at 20 Hz repetition rate. No failure has occured yet.

REFERENCES

1. W. Schnell, Proc. International Conf. on High Energy Accelerators at Dubna 1963, p. 927.
2. Design Study of a 300 GeV Proton Synchrotron AR/Int. SG/64-15, 1964.
3. R. Billinge, W. Schnell, Contribution to this Conference.

DISCUSSION (condensed and reworded)

L. Smith (L.R.L.): Was the tuner driven by eddy currents induced in the moving cylinder?

Schnell: No, the driving action was that of a moving coil loudspeaker with stainless steel strip connection to the coil.

H.E. Stier (Bonn): What is the maximum tuning range at 50 Hz?

Schnell: 15 mm is the sinusoidal movement at 50 Hz, in the tuner life test without cavity. This gives similar velocity and acceleration as in a real frequency program at 20 Hz.

E.M. Rowe (PSL): Will your servo speed be fast enough to be capable of controlling synchrotron oscillations?

Schnell: No, the tuning servo bandwidth is 3 kc maximum, and faster control must be on the rf frequency and amplitude only.

M. Plotkin (BNL): What is the mechanical length of your cavity and what is its electrical length?

Schnell: It is 25 cm long; lambda/4 is 40 cm, therefore the shortening is 15 cm.

M.C. Crowley-Milling (Daresbury): How do you effect the Q change from 1700 at injection to 5000 later?

Schnell: A 50 ohm resistor is loop-coupled to the cavity via a frequency dependent line.

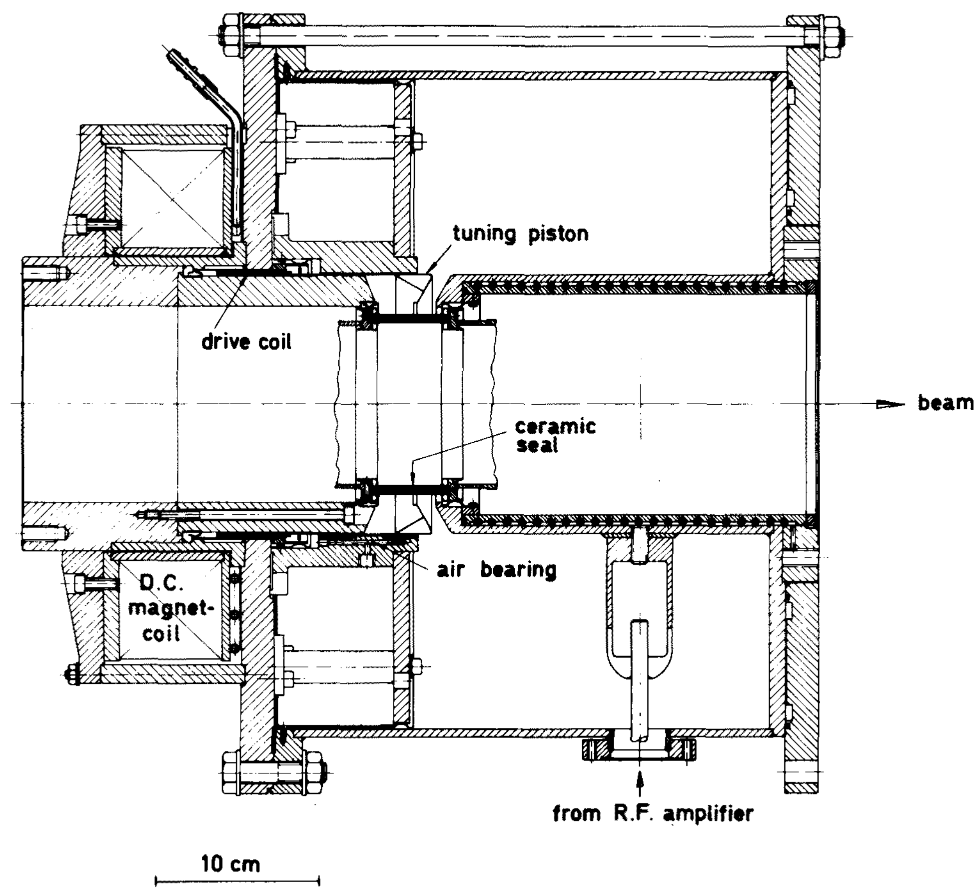

Fig. 1 : Cross-section of the cavity.

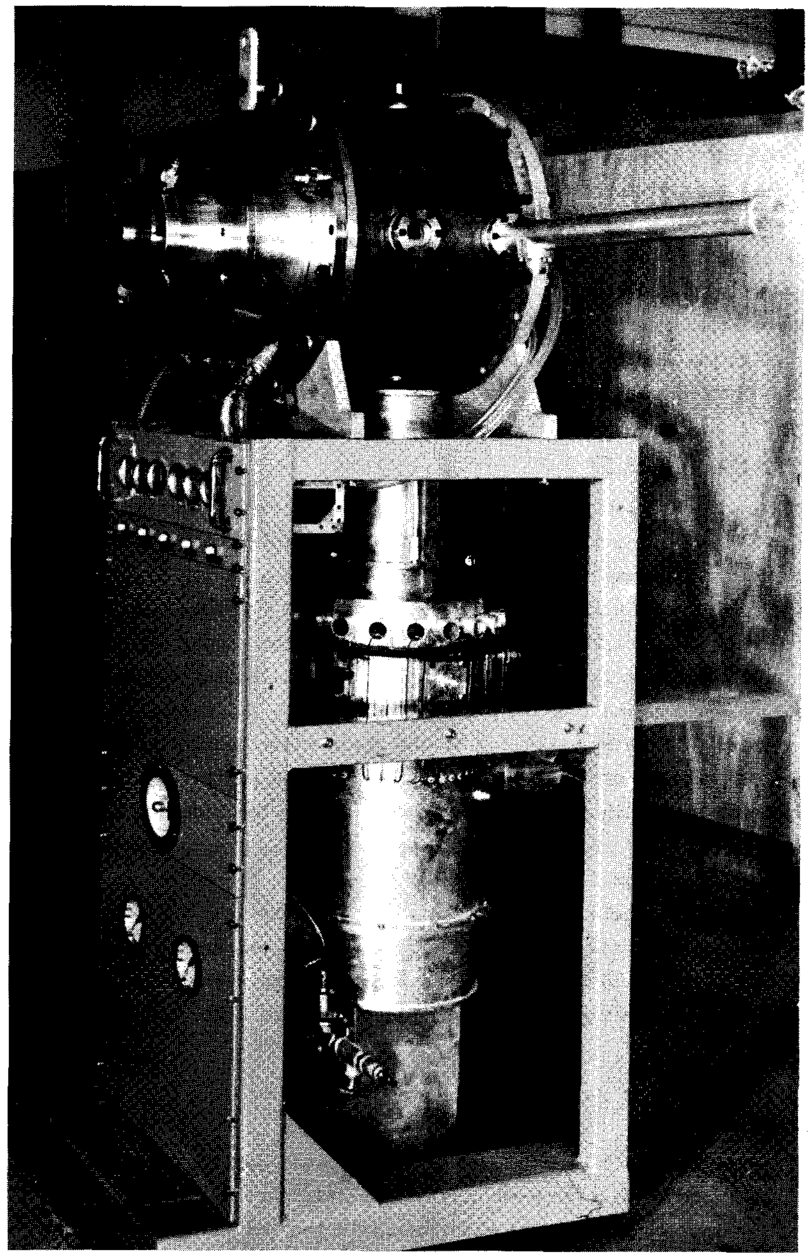

Fig. 2 : The cavity with its power amplifier.