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Design report for the capacitive tuners of the 80 MHz cavity.

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1. Introduction.

The strategy for the tuning of the 80MHz cavity has been decided taking into account the following factors:

1. as for the 40MHz cavity, there will not be a fast tuner to compensate for beam loading effects. Since a heavy beam loading will occur during operation, the power amplifier has been designed to partially cope with it [1];

2. the deformation due to atmospheric pressure on the cavity under vacuum has been calculated using a FEM code [2] and its effect, calculated with SUPERFISH, is to *shift down* the cavity frequency by 0.2%;

3. the effect of *atmospheric pressure variations* can be considered to be a small fraction of the effect above. A variation of ±1% of the atmospheric pressure will cause a frequency change of:

$$\frac{\Delta f}{f} = \pm 0.02\% \,;$$

4. the deformation due to heating of the cavity under CW operation in presence of water cooling has been again calculated with the help of J. Genest [2]. The effect on the cavity frequency will be to shift it *up* of 0.2% at the thermal regime;

5. because of water cooling we can assume that there will be no sensitivity on atmospheric temperature variations;

6. the effect of mechanical imprecision, of the holes for the ports, of the imprecision of MAFIA and SUPERFISH can be estimated less than ±0.1% in frequency.

7. the shift in frequency due to the amplifier loading, which is not negligible for the overcoupled amplifier needed. The amplifier coupling loop will shift up the frequency of the cavity by ~0.7% [3].

According to the above specifications, it has been decided to use two mechanisms:

- a *coarse* tuner to compensate the effects 2, 6 and 7;
- a *fine* tuner moved by a servomechanism to compensate the effects 3 and 4.

In the following the concept of the chosen tuners is explained, and the effect expected will be presented and compared with measurements done on the TRIUMF wooden model.

2. Design of the tuners.

There are basically two types of tuners: inductive tuners, which can only shift the frequency *up*, and capacitive tuners, which can only shift the frequency of the cavity *down*. The choice between them depends on the position of the frequency of the loaded cavity with respect to the frequency of operation. For the 80MHz cavity the frequency of operation is 80.11 MHz.

The frequency given by SUPERFISH simulations is 80.28 MHz. This frequency is not really a free parameter because of the environment around the cavity (e.g. the mechanical short circuit), which put serious constraints on the cavity geometry.

The presence of the ports for vacuum pumps, coupling of amplifier and HOM dampers can be estimated with the help of SUPERFISH and is taken into account in point 6 of the preceding section.

In addition, there will be a shift of the frequency, as written in point 7, of +0.7% due to the amplifier loop, and another due to vacuum of -0.2%.

The only logic choice is then to use capacitive tuners since *the frequency of the loaded cavity will be at least 0.6% above the frequency of operation.*

A sketch of the cavity with one tuner is shown in fig. 1:

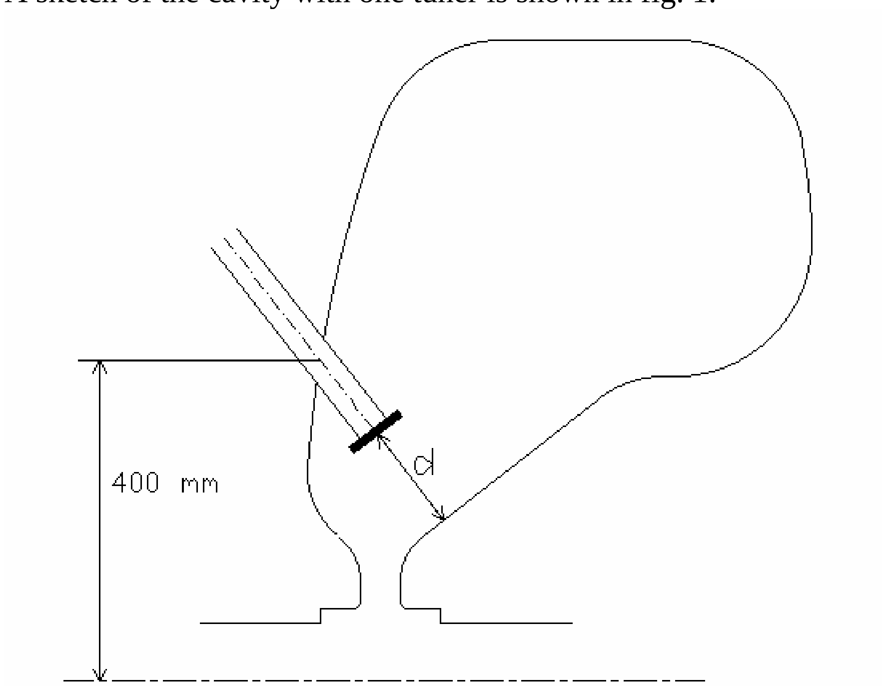

Fig. 1: *The 80 MHz cavity tuner.*

The tuners are made from a circular rod sliding through the cavity wall from one side, supporting a circular plate of 75 mm diameter which is parallel to the opposite side of the cavity wall. The position of the tuner has been chosen to be as close as possible to the gap, in order to have a high voltage on the tuner gap, to avoid multipactor.

A 3D simulation of this device has been performed with MAFIA. The result is not very accurate because it is not possible to mesh properly the 3D geometry with the tuner. In particular the simulation assumes a wider rod with a square cross section, with an approximately square capacitive plate at the end whose dimensions are a little bit larger than the real plate. The frequency change due to the cavity calculated by MAFIA is then about the double than that measured on the TRIUMF wooden model.

The integral of the electric field along the axis of the tuner from one side of the cavity wall to the other is about 98% of the integral of the electric field along the gap. Thus the step up ratio between the gap voltage and the voltage on the tuner is very close to 1. A simplified equivalent circuit of the cavity-tuner system is shown in fig. 2.

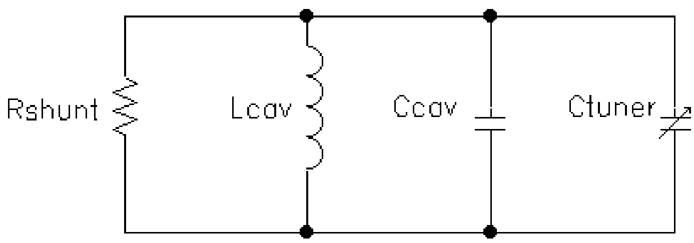

Fig. 2: *The equivalent circuit for the cavity-tuner system.*

The significance of Rshunt, Ccav and Lcav is trivial, Ctuner has been calculated, in first approximation, as:

$$\text{Ctuner} = \frac{\varepsilon_0 \cdot A}{d} \qquad (1)$$

where $A=\pi \cdot r^2$, *r* is the plate radius and *d* is the tuner gap distance (fig. 1). Using relation (1) a trade-off between *r* and *d* values has been found to have a plate which could pass through a standard dimension port, and at the same time to have it not too close to the gap in order not to disturb too much the electric field path on the cavity gap.

A more accurate circuit should take into account first of all that the real geometry of the tuner is not a plane capacitor, but also the variable inductance of the rod and the variable straight capacitance of the plate to the cavity walls. Therefore the dependence of Ctuner on *A* and *d* is with no doubt much more complicated than the simple relation (1). Indeed the measurements done on the TRIUMF wooden model [3] showed that in reality Ctuner is not linear with *d*, due to the effects neglected. A plot of the measured effect on the frequency is reported in fig. 3. More information on the measurements on the wooden model can be found in [3].

Anyway for the precise design of the tuner the knowledge of the detuning in the two extreme positions of the tuner is sufficient. The rest position and the dependence of the detuning from *d* will be determined during RF tests on the real cavity (Sep. '97).

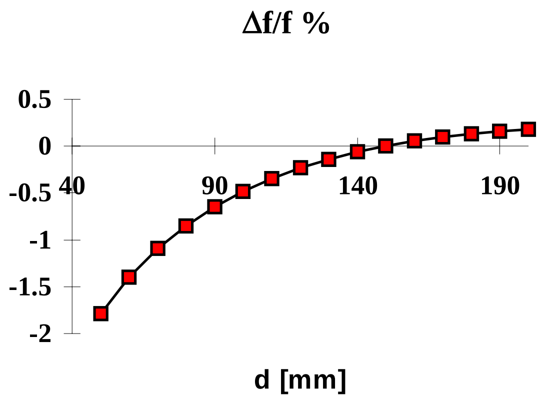

Fig. 3: *Detuning measured on the wooden model, referred to the detuning measured at d=150 mm.*

Referring to wooden model measurements, which is the most accurate result we have for the moment, we have:

f_0=79.412 MHz (no tuner)

f_1=79.319 MHz (one tuner with d=170 mm and r=37.5 mm; position of minimal detuning)

f_2=78.380 MHz (one tuner with d=90 mm and r=37.5 mm; position of maximal detuning)

The rest position for the fine tuner will be determined as the distance for which:

$$f = \frac{f_1 + f_2}{2} \quad (2)$$

The rest position for the coarse tuner will be arranged such that:

$$f = 80.11 \text{ MHz} \quad (3)$$

The tuning range provided by each of the tuners will be approximately:

$$\frac{f_1 - f_2}{f} \% \approx 0.8\% \qquad (\pm 0.4\%) \quad (4)$$

The detuning introduced by the ***two*** tuners at the nominal rest position is:

$$2 \cdot \frac{f_0 - f}{f} \% = -0.8\% \quad (5)$$

Since, as written above, the frequency of the cavity without the two tuners is at least +0.6% above the frequency of operation, the frequency of the loaded cavity plus the two tuners at the rest position should be quite close to the frequency of operation.

The total tuning range offered by this tuning system (±0.8%) gives already enough margin against every “surprise” could occur after the first RF test.

If the surprise will be more than reasonably expectable, there are in any case at least four ports free which can be used to put some more tuning devices, both capacitive or inductive.

Let’s estimate now the current in the tuner for the position of maximal (d=90 mm) and minimal (d=170 mm) detuning. The capacitance Ctuner can be calculated as follow:

$$\mathrm{Ctuner}_{\mathrm{MAX}} = \frac{1}{\mathrm{Lcav}} \cdot \left(\frac{1}{\omega_2^2} - \frac{1}{\omega^2} \right) \approx 0.6\,\mathrm{pF} \quad (6)$$

$$\mathrm{Ctuner}_{\mathrm{MIN}} = \frac{1}{\mathrm{Lcav}} \cdot \left(\frac{1}{\omega_1^2} - \frac{1}{\omega^2} \right) \approx 0.04\,\mathrm{pF} \quad (7)$$

With a gap voltage of 200 kV the current on the rod in the two cases is:

$I_{\mathrm{MIN}} \approx 3\,\mathrm{amp}$; $I_{\mathrm{MAX}} \approx 60\,\mathrm{amp}$

Assuming a resistance of 20 mΩ[I] for the rod the mean power dissipated in the two cases is:

$$P_{\mathrm{MIN}} = \frac{1}{2} R I_{\mathrm{MIN}}^2 \cdot d_\tau \approx 0.1\,\mathrm{Watt}; \qquad P_{\mathrm{MAX}} = \frac{1}{2} R I_{\mathrm{MAX}}^2 \cdot d_\tau \approx 18\,\mathrm{Watt} \quad (8)$$

The duty cycle value used in (8) is 50% to take into account the fact that the nominal gap voltage of 200 kV is held only for a part of the cycle. This amount of power doesn’t require a specific water cooling.

It is interesting to note that this amount of power is negligible compared to the 6 kWatts dissipated on the cavity walls, so the shunt impedance will not be reduced by the introduction of the tuners. With reference to the circuit of fig. 2 it results:

$$\frac{dQ}{Q} = \frac{1}{2} \cdot \frac{dC}{C} \quad (9)$$

where C=Cav+Ctuner. From (6) and (7) results that the change in the Q factor is negligible. This conclusion has been confirmed by measurements of Q on the TRIUMF wooden model for different values of *d* [3].

It is worth noting also that the two extreme positions are not likely to be assumed by the tuners. In fact for the coarse tuner the position is fixed once for all.

[I] The resistance at 80 MHz due to skin effect of a rod of 40 mm diameter, 200 mm long is ~4mΩ.

The fine tuner, which will be connected to a feedback loop, will move only during the initial transitory of the cavity towards the thermal regime. Movements for atmospheric variations are negligible (see Sec. 1). At least during the first year the cavity will not work at CW. So further adjustments of the tuners or additional tuning systems can be studied, if needed, to reduce the maximum current on the rod, or to improve the tuning range.

One convenient modification to the tuner is for example to reduce the diameter of the capacitive plate, which can be done *with a simple machining of the plate*. If the tuning range, as it appears from the calculations above and from the measurements on the wooden model, is much more necessary the diameter of the plate can be reduced to an optimum size which can be determined only by measurements on the real cavity.

3. Mechanical design.

It has been decided to design a piston mechanism of the same type used more or less everywhere on the RF systems of LINAC II and LINAC III, for the following reasons:

- to avoid a totally new mechanical development;
- to profit of the experience of maintenance which is already acquired in the group;
- they have worked for ten years without any important fault;
- the possibility to share some spare components with the LINAC section.

A sliding contact has been provided between the piston and the cylinder to protect the bellows from RF currents, even if the piston and the cylinder form a capacitance of large value, which should already make a good protection. The presence of a contact sliding in the vacuum doesn’t seems to be a problem from the point of view of the vacuum because of the slowness of the movement [4].

4. Conclusions.

The tuning strategy for the 80MHz cavity has been defined after an analysis of all the factors which could cause a frequency shift. Typical problems of tuners like multipactor, heating and mechanical reliability have also been considered.

The solution proposed is to tune the cavity by means of two identical devices whose effect is to add a variable capacitance to the cavity and to shift the frequency of the cavity down.

The expected tuning range is, in total, ±0.8%, without any relevant change of the Q factor. This value can be considered quite reliable since it has been measured on the TRIUMF wooden model.

The devices can still be modified to fit the needs of tuning if the first RF tests should give results different from the guess values listed in section 1. In any case some additional ports have been provided on the cavity to permit the introduction of other tuners.

5. References.

[1] D. Grier, private communication.

[2] J. Genest, private communication.

[3] R. Losito, A. Mitra, *Measurements and simulations on the 80 MHz wooden model*, PS/RF Note 96-31.

[4] C. Burnside, private communication.

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