6-28-91
James E. Griffin
C. Bhat

PROPOSAL FOR EXPERIMENTAL TEST OF RF HARMONIC TRANSITION CROSSING IN THE MAIN RING

Introduction.

A technique for minimizing longitudinal emittance growth during transition crossing has been described in Main Injector note 0055. The procedure requires the addition of a component of second or third harmonic rf to the fundamental rf wave for a period of tens of milliseconds spanning transition time. This document outlines a procedure for testing the technique in the Main Ring by the installation of a single 159 MHz (third harmonic) rf cavity . Use of the second harmonic is favored from a performance point of view but substantially more second harmonic component is required than third harmonic so that more and larger rf cavities would be required if second harmonic were to be used. Several ESME simulations (Appendix 1) have indicated that substantial improvement in transition crossing can be expected in the Main Ring for bunches with longitudinal emittance up to 0.5 eV-s using a single third harmonic rf cavity.

The salient feature of this procedure is that the rf system should supply precisely that voltage required to accelerate all of the particles in each bunch at the rate dictated by the rate of rise of the guide field. This would require a voltage wave which is constant in amplitude over the phase range occupied by particles. Such a wave can be developed to sufficient precision by a sum of fundamental and third harmonic:

$$V(t) = V_1[\sin(\omega t) + 0.1295\sin(3\omega t)] \tag{1}$$

where V_1 is the amplitude of the fundamental component.

We assume here that γ_t=19, (cp(t)=17.8 GeV/c), and that the momentum varies parabolically following injection until an energy substantially higher than transition is reached. With t=0 at the start of the parabola, the momentum during the parabola is

$$cp(t) = 8.889 + 200t^2 \qquad GeV/c. \tag{2}$$

where $F_\infty = c/C$.

The required <u>accelerating</u> voltage at any time is,

$$V_{acc} = \frac{1}{F_\infty}\left[\frac{d(cp)}{dt}\right] \tag{3}$$

Transition occurs at 0.211 s, at which time the required accelerating voltage is 1.769 MV.

The fundamental rf phase is to be adjusted so that the center of the bunch passes the accelerating gaps at $\omega t=\pi/2$ during the transition crossing period. Using Eq.1 we find that the fundamental voltage V_1 must be 2.03 MV and the third harmonic voltage V_3 must be 261 kV at transition.

We expect the non-focussing transition crossing period to extend approximately ±15 ms around transition time, i.e. from 0.196 to 0.226 seconds after the start of the parabola. Several useful parameters are listed below for these times.

Time	cp(GeV/c)	d(cp)/dt	gamma	beta	F_0(kHz)	V_1(MV)	V_3(kV)
0.196	16.57	78.4×10^9	17.69	0.9984	47.637	1.886	244
0.211	17.8	84.4×10^9	19	0.9986	47.647	2.03	261
0.226	19.1	90.4×10^9	20.38	0.9988	47.656	2.175	281

TABLE 1. Machine parameters at transition and at t_t ± 15 ms.

The third harmonic rf system will be required to provide 244 to 281 kV while tuning from 159.059 to 159.123 MHz for a 30 ms period around transition on each accelerating cycle. The system must have the additional property that it will not disturb the accelerated beam through its fundamental or harmonic resonance impedances at other times during the acceleration cycle. We propose to use a single rf system consisting of a modified 200 MHz CERN LEP injector rf cavity

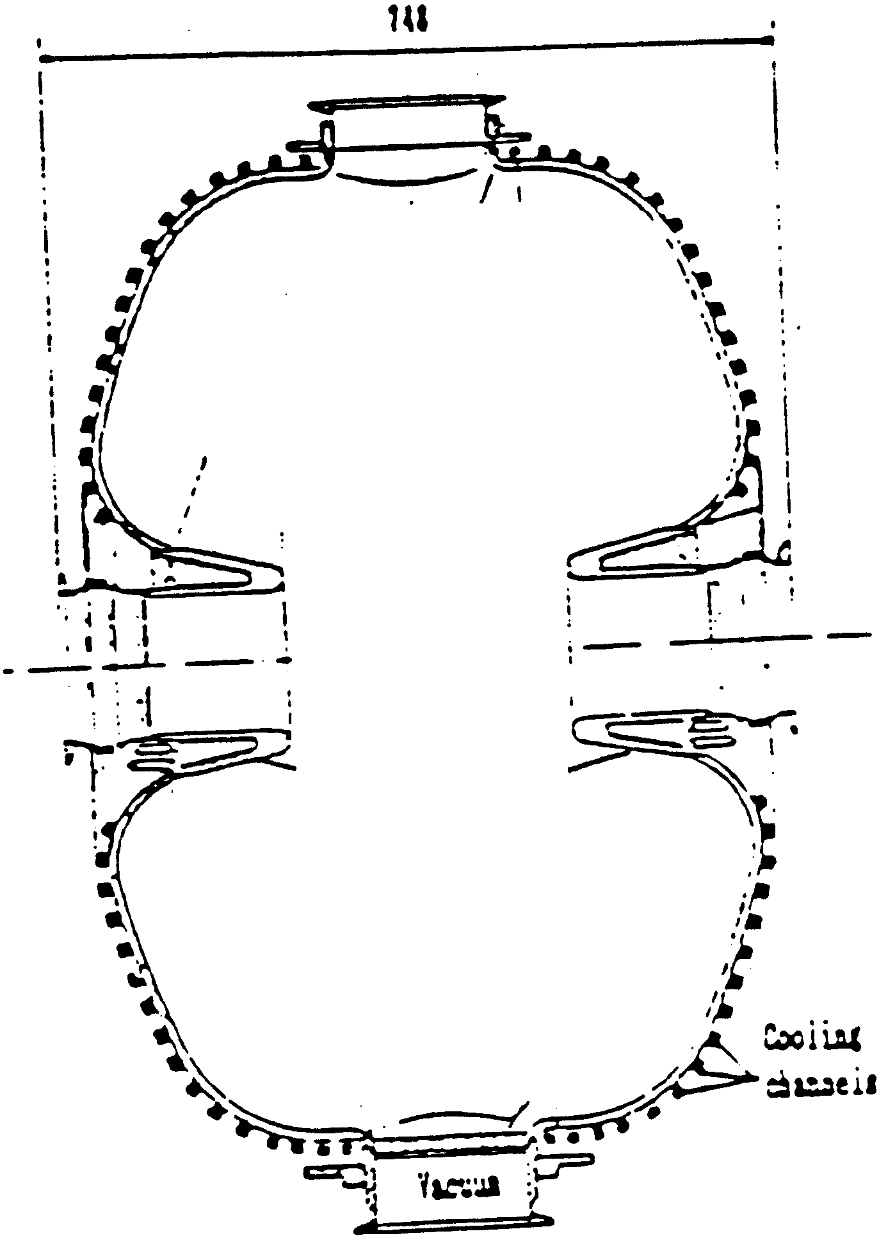

Figure 1. Cross section of the CERN 200 MHz single cell cavity.

driven by the third harmonic component from a slightly modified Tevatron rf power amplifier. It has been established that this rf cavity can be mounted with its axis on the Main Ring beam line in such a way as not to interfere with the Tevatron beam pipe (provided that there is no Tevatron magnet or rf cavity at that location).

THIRD HARMONIC CAVITY.

Details of a 200 MHz rf system used for lepton acceleration in the CERN SPS are described in Appendix 2. The cavities are made of copper and designed to provide 1 MV accelerating gradient when excited by a locally mounted rf power amplifier delivering about 50 kW. Initial calculations on the cavity indicated R/Q > 200. Completed assemblies have measured R/Q about 175 with shunt impedance about 8.5 MOhm. The cavity has six access ports around its periphery for input power coupling, pumping, spurious mode damping, tuning, etc. The particular cavity which is available for our use has a slightly smaller gap spacing than specified (269 mm instead of 288 mm) and its interior has been treated with titanium for multipactor studies. Both of these anomalies appear to be to our advantage. We find that the reduced gap spacing reduces the cavity center frequency to near 195.5 Mhz (unless the cavity has other geometric anomalies which we don't know about). A cross section of the cavity is shown in Fig.1.

For our purpose it will be necessary to reduce the cavity operating frequency to 159 MHz and to provide some mechanism for tuning the cavity electronically over a range of 65 kHz during operation.

It should be possible to reduce the cavity frequency by deforming the cavity along its axis (squeezing) to increase the gap capacitance. Superfish calculations have been done to determine the extent of squeezing necessary to reduce the frequency to 159 MHz. The results are shown in Fig.2. It would be necessary to reduce the gap spacing from 26.9 cm to 11.24 cm. This amount of deformation appears to be excessive and might result in damage to the weld seams which run azimuthally around the cavity. Because of this risk we propose an alternative method of adding to the cavity gap capacitance.

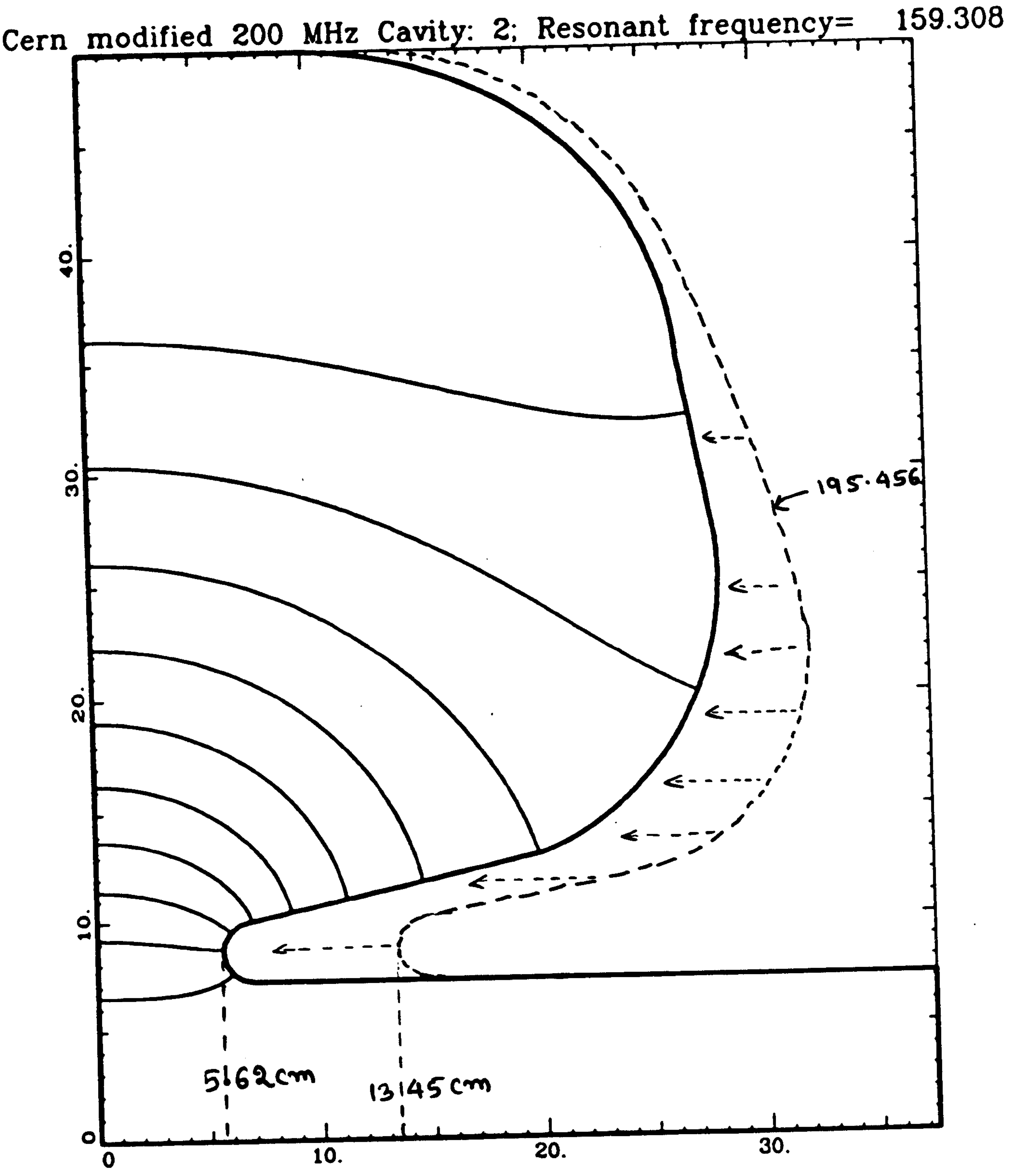

Figure 2. The dashed line is the initial cavity contour. The solid line shows the extent of longitudinal squeezing necessary to lower the cavity frequency to 159 MHz.

In order to reduce the cavity frequency by the required amount we propose to insert an annular metal ring between the nosecones of the cavity as shown in Fig.3. Such a ring will increase the gap capacitance and accomplish the required frequency reduction.

In Figures 4 and 5 we show Superfish and Mafia plots of the fields in a one quarter section of the original cavity with an annular metallic ring (donut) inserted midway between the nosecones. This reduces the frequency by the required amount with no change in the cavity geometry. Such a ring could be suspended by a heat conducting rod extending from one of the access ports. Because there is no way to insert such a ring intact into the cavity, the ring will have to consist of two halves which are joined in some (yet undetermined) manner after the halves are inserted into the cavity through the beam pipe. The use of an annular ring as shown has the added advantage that it may be possible to place a dc potential on the ring to inhibit multipactoring in the gap region of the cavity.

Either of the methods for frequency reduction will have some effect on the Q and the shunt impedance of the cavity. The R/Q of a resonant structure is proportional to the capacitive reactance of some equivalent capacitance related to the gap capacitance, (i.e. inversely proportional to the electrical stored energy). An estimate can be made of the effect on R/Q of reducing the frequency by squeezing or otherwise adding to the effective gap capacitance. Approximate relations are:

$$\frac{\Delta f}{f} = -\frac{1}{2}\frac{\Delta C}{C} = \frac{1}{2}\frac{\Delta (R/Q)}{(R/Q)} \tag{4}$$

$$\Delta\frac{R}{Q} = 2\frac{R}{Q}\frac{\Delta f}{f}$$

For Δf/f=0.185, the cavity R/Q should be reduced to from 175 to 110, but this formalism is probably inaccurate for incremental values as large as those under consideration. In fact, the Superfish result for the squeezed cavity indicate a decrease in R/Q of about 29 percent with a resultant value of 124. The annular ring result indicates about a 19 percent decrease, to about 142. In each case a decrease in Q of about 15 percent was indicated. The addition of mode dampers, ferrite tuners, and other ancillary equipment to the cavity will reduce the Q a bit more without substantially changing the R/Q. We estimate that

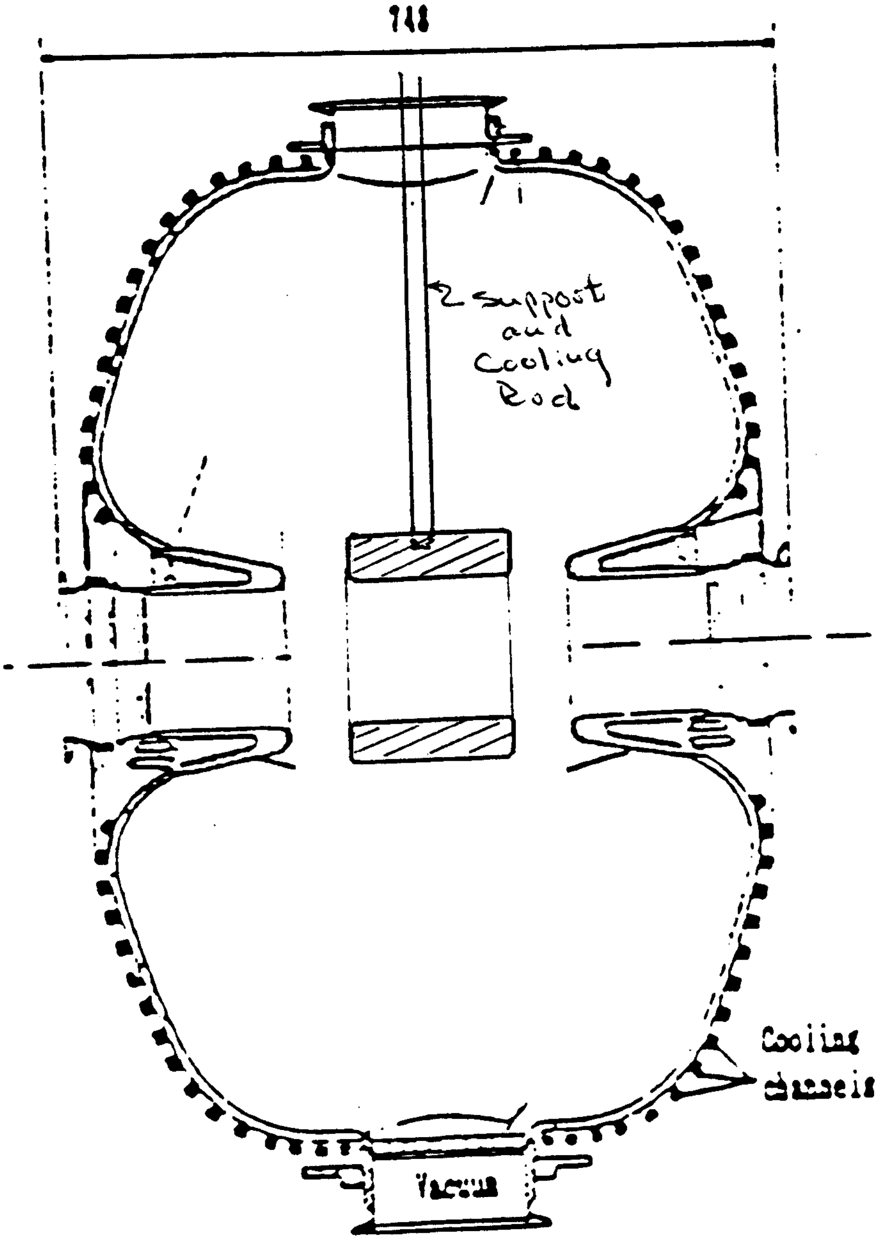

Figure 3. Modification of the CERN cavity by insertion of metallic annulus between the nosecones. The resonant frequency is reduced to 159 MHz.

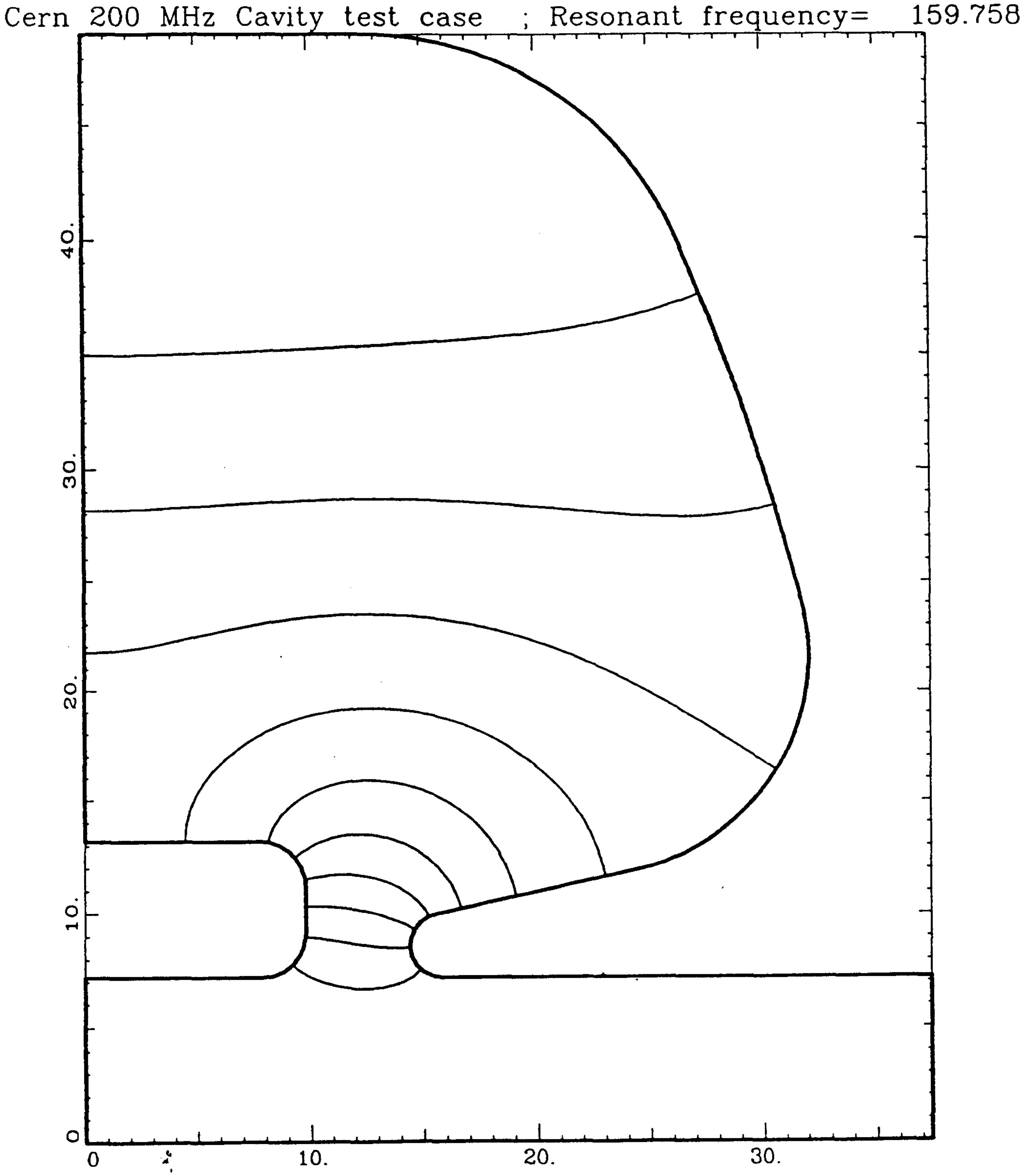

Figure 4. Superfish plot of fields in modified cavity with resonant frequency 159 MHz.

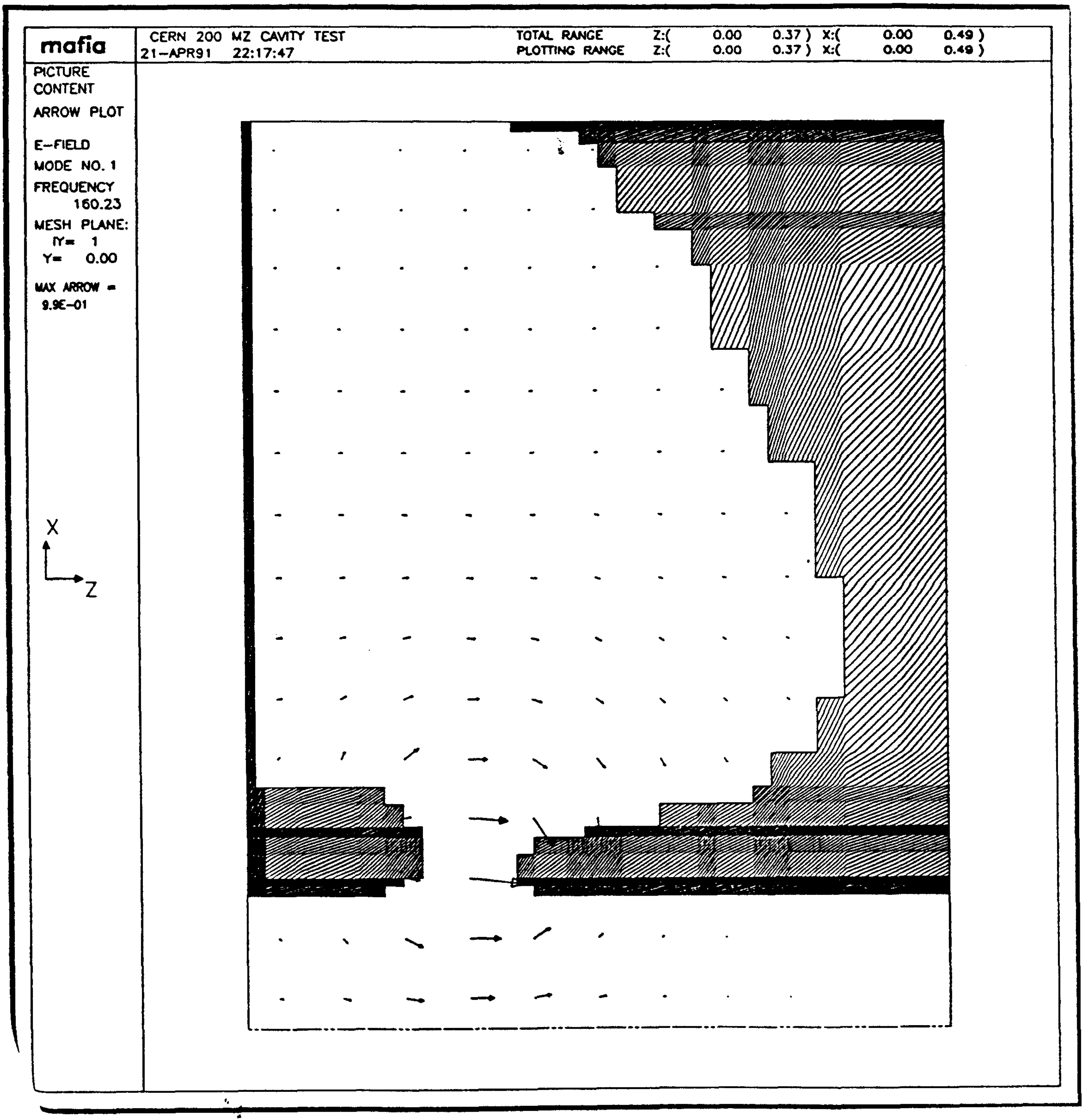

Figure 5. Mafia plot of fundamental fields in modified cavity with resonant frequency 159 MHz.

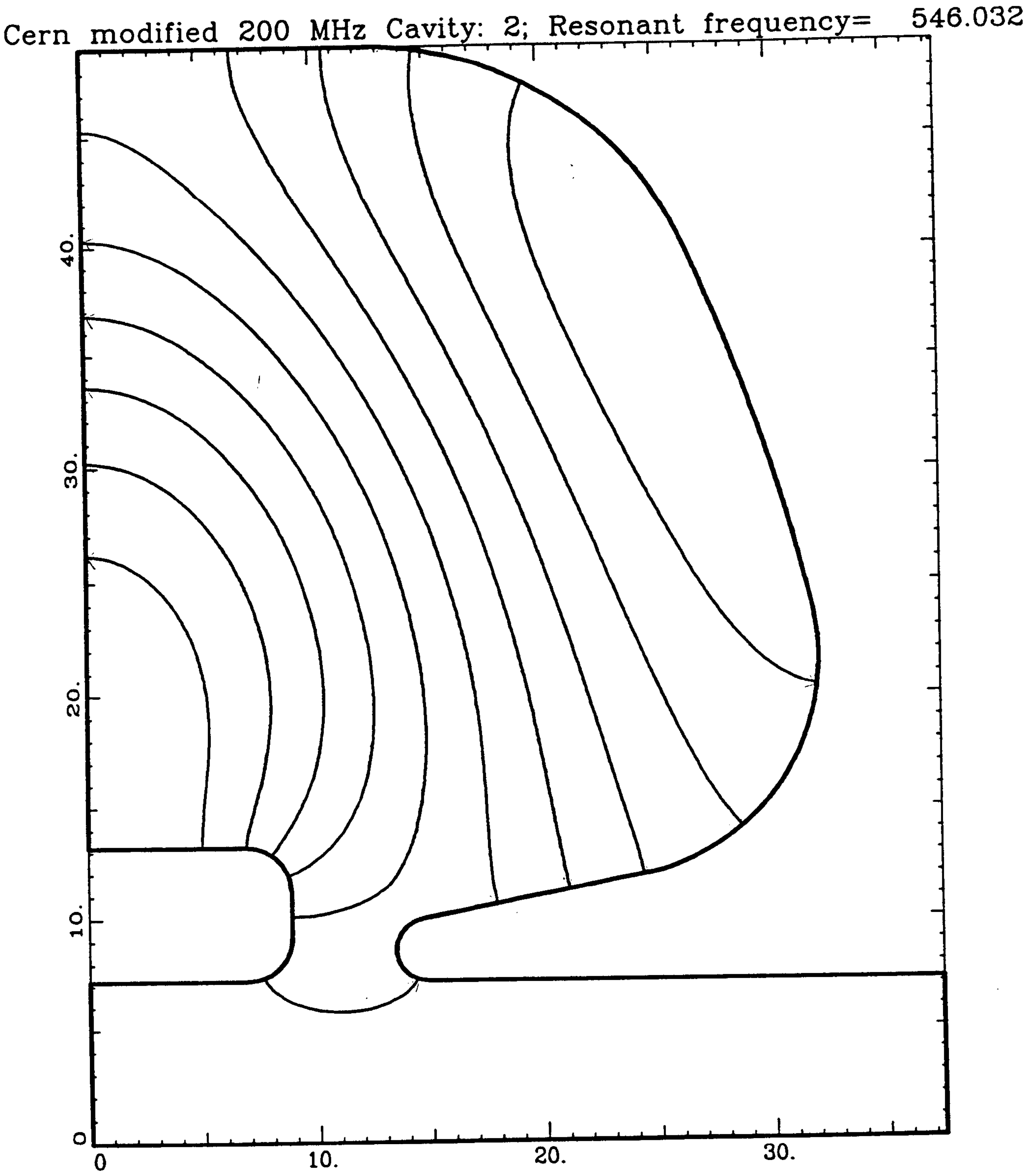

Figure 6. Superfish plot of fields of the lowest longitudinal higher order mode in the modified cavity.

the resulting structure will have a Q of 35000 and gap shunt impedance about 5 MOhm. The maximum electric field strength in the cavity is on the nosecones, and with the frequency reducing annulus in place the field does not exceed 5 MV per meter at the metallic surface for a gap voltage of 280 kV. This is a relatively small field and should cause no problems with discharge or sparking.

The first strongly coupled longitudinal higher order mode of the ring loaded cavity occurs near 546 MHz. A Superfish plot of the fields is shown in Fig.6. It may be necessary to damp this mode selectively. Other higher order modes may be adequately damped during acceleration away from transition by removing the bias field from the ferrite tuner when the cavity is not in operation.

TUNING THE CAVITY

The cavity will operate on harmonic number 3339 and the operating frequency range will be 159.059 to 159.123 MHz. This frequency swing, 64 kHz, is an order of magnitude larger than the natural resonance width of the cavity so it will have to be tuned dynamically during the transition crossing period. We propose to tune the cavity using orthogonaly biassed rings of Iron-Yttrium-Garnet high frequency low loss ferrite. The rings will be incorporated into a short coaxial transmission line and inductively coupled to the high magnetic field region of the cavity through one of the existing access ports. Saturation and tuning bias can be applied to the ferrite by wrapping a solenoid coil around the outside of the tuner. This ferrite has the property that it has a relatively high Q (1500-2500) when biassed but an extremely low Q when unbiased. Use of this type of ferrite is described in several papers included in Appendix 3.

Tuning is accomplished by changing the ratio of electric to magnetic stored energy in the cavity. With gap voltage 270 kV the time averaged stored energy (equal to the <u>peak</u> value of the magnetic stored energy) is approx. 0.25 J. From this and the required frequency swing one can find the amount of energy required to be stored in ferrite using Slater's (or Foster,s, I can,t remember which) tuning theorem.

$$\frac{\Delta W_m}{W_m}=2\frac{\Delta f}{f} \qquad (5)$$

With Δf/f 4 x 10^{-4} and 0.25 J stored energy, the required change in magnetic stored energy is 2 x 10^{-4} J. Since it is not possible to force <u>all</u> of the stored magnetic energy out of the ferrite by biassing, it is necessary to store some additional energy in ferrite. We assume here that it will be sufficient to store 5 x 10^{-4} (peak) J of magnetic energy in the ferrite. Assuming that the Q of the ferrite is 2000, this means that the ferrite must dissipate approx. 175 watts during the period of operation. Since the duty factor of this rf system is extremely small it is not unreasonable to allow the ferrite to dissipate 0.5 watts per cc during operation. Thus a total volume of ferrite of 350 cc will be required. We have acquired from AEC Canada, Chalk River, Ont. three Trans-tech G810 cores 12.7 cm O.D., 7 cm I.D. 1.27 cm thick, volume 112 cc. These cores should be adequate to build the required tuner.

The cores can be configured in a coaxial geometry with thin copper septa between them extending to an outer copper cylinder which can be cooled by longitudinal conduction to water cooling coils at the shorted end. The inner conductor of the coaxial line might have a 2 cm radius, providing 1.5 cm spacing between inner and outer conductor for voltage hold-off. Because the biassing field is to be provided by a solenoid encircling the entire structure, the outer can and the cooling septa can be slotted longitudinally to minimize eddy currents and improve the tuner time constant in response to a change in bias current. The center conductor of the tuning coaxial line will be inductively coupled to the high magnetic field region of the cavity. Either the entire tuner will have to be evacuated or an rf window vacuum seal will have to be placed around the center conductor. If the rf window option is not used, the flux slots will have to be made vacuum tight. Neither option sounds attractive so maybe some third option can be conceived.

A quick calculation of the tuner inductance (as seen by the cavity) is 25 nH when the incremental permeability of the ferrite is 3.5. Since ω is conveniently 10^9, the inductive reactance is j25 Ohms. At this permeability the time averaged stored magnetic energy in the tuner is to be 0.35 mJ so the required rf current is 167 A (assuming the tuner represents a lumped inductor). This requires a tuner voltage of 4175 volts. Using R/Q 142 and 280 kV gap voltage we estimate the peak B field at the outer edge of the cavity to be 8×10^{-4} W/m^2. With this field the required tuner voltage can be developed in a semicircular loop of radius 6 cm. These calculations are not meant to be precisely accurate but only to show feasibility of the proposed design.

We estimate that a field of 0.2 W/m^2 (2000 Gauss) will be required to bias the ferrite to a relative permeability of 1.5. If a Fermilab bias supply is used to provide this current we reasonably limit the peak current to 2500 A. This will require about one turn per cm of water cooled conductor over the approx. 10 cm length of the tuner can. It may be necessary to place a flux return yoke of laminated iron, Metglas, or ferrite around the entire assembly. Also a flat (reverse current sheet) winding at each end of the tuner may be useful in limiting the extent of the biassing field and thus reducing the inductance presented to the bias supply. However, the very small amount of ferrite in the tuner compared to a Fermilab style tuner would seem to indicate that load inductance presented to the bias supply may actually be too small for stability and some additional inductance such as a spare Main Ring tuner may have to be placed in series with this tuner. A sketch of the proposed tuner geometry is shown if Fig.7.

POWERING THE CAVITY

With shunt impedance of 5 Mohms, the cavity will require an excitation current (transformed to the gap) of 56 mA. The excitation power will be 7.84 kW. In Appendix 4 it is shown that a standard Fermilab power amplifier, driven at the fundamental frequency and properly coupled to the cavity has the capability of delivering sufficient third harmonic current to excite the cavity to full amplitude.

However, the problem is perhaps not how to drive the cavity from an external source but how to control the amplitude at the required level during transition crossing with beam in the machine. The required phase of the third harmonic component is such as to subtract from the amplitude of the fundamental wave at the peak of the wave

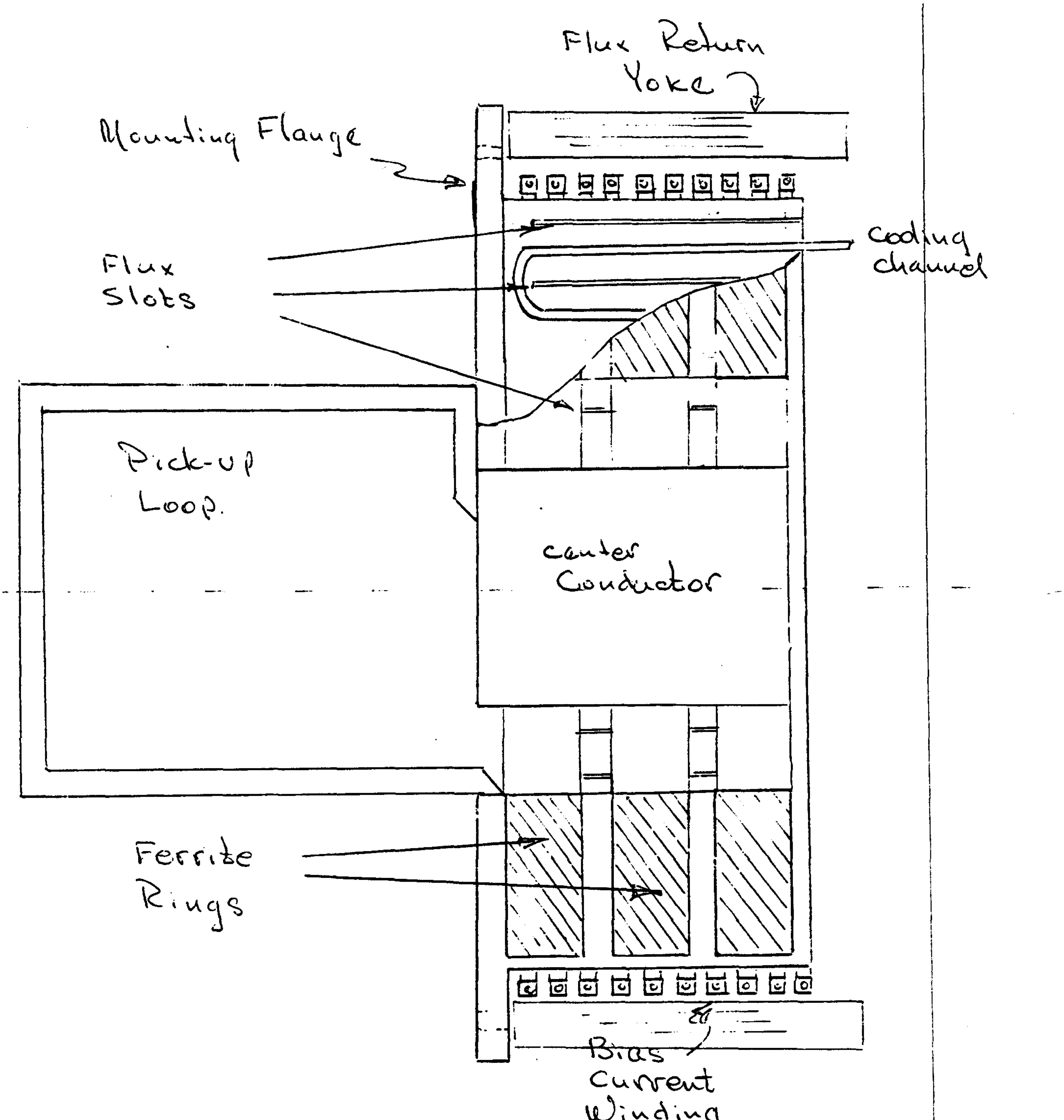

Figure 7. Cross section sketch of tuner showing ferrite cores, cooling wafers, flux slots, bias winding and flux return yoke.

(i.e. $\varphi_s = \pi/2$). If the cavity is tuned exactly to resonance the voltage induced in the cavity by the beam image current will be exactly the correct phase. At beam intensity 4 x 10^9 protons per pulse the dc beam current is 34 mA. At this relatively low intensity the beam will have a Fourier component at 159 MHz adequate to excite the cavity to the required level. At higher beam intensity the cavity will be overdriven by the beam if some means is not employed to take energy out of the cavity (i.e. decrease the cavity Q).

The amplitude might by controlled by driving the cavity in the opposite phase with current from the power amplifier. This would amount to removing energy from the cavity and depositing it in the power tube anode, as is done in the Antiproton Debuncher Ring. The exact amplitude could then be controlled by controlling the phase and drive amplitude in the power amplifier. An alternative method might be simply to control the energy deposited in the tube anode by adjusting the dc current in the tube (cascode current) with no rf excitation. This would result in a more uniform deposition of energy in the tube anode since the voltage swing at the anode would be the same on each third harmonic cycle. Essentially the power amplifier is used as a variable real load impedance presented to the cavity.

The program for controlling the amplitude is to be is to be derived by measuring the amplitude of the fundamental fanback signal during transition crossing and setting the third harmonic amplitude to be some fixed fraction, (nominally 0.129) of the fundamental.

TOTAL AMPLITUDE CONTROL, RADIAL POSITION

During non-focussing transition crossing the total flat-topped rf amplitude must be exactly that required for acceleration of the beam. If the amplitude is incorrect a growing momentum error will be introduced which, in time, will evidence itself as a radial position error.

$$\frac{\Delta R}{R} = \frac{1}{\gamma_t^2}\frac{\Delta p}{p} \qquad (6)$$

During normal operation the radial position error signal is delivered to a phase shifter in the low level rf system along with a program signal which sets the synchronous phase angle φ_s. Momentum errors are corrected by adjusting the synchronous phase angle for more or less accelerating voltage as required. The transition phase jump is accomplished by switching the drive phase by π radians and reversing the sign of the phase shifter drive signal so that the original phase of $\varphi_s+\varphi_e$ becomes $\pi-\varphi_s-\varphi_e$ as required. Because the sign of the error signal is changed at transition the radial position loop accomplishes the required change in accelerating voltage in both regimes. The loop gain of the system is programmed in a manner unique to the present transition crossing dynamics.

Because we expect to operate with a flat-top rf wave spanning the bunch time spread during transition crossing it would appear that the existing system would not work during this period and that the error signal would somehow have to be delivered to the rf amplitude program, perhaps via the "anode program". We propose here a method of amplitude control which will require almost no change in the existing radial position control procedure. We assume that the rf cavities are divided into two equal groups of perhaps sixteen cavities each. The two groups are driven from the same frequency generator in the low level system but through two separate phase shifter systems, including separate π radian shifters for transition phase jump. The same program and error signals are delivered to each of the phase shifters but the π radian phase jump and sign change can be done separately at different times. At the beginning of the transition crossing period one group of cavities is shifted from below to above transition in the normal manner while the other group remains below transition. This results in an effective shift of the rf phasor sum of all cavities to $\pi/2$ radians as required, with no change in amplitude. At the same time the third harmonic system is turned on. This necessitates a slight increase in the fundamental amplitude which can be accomplished by introduction of a radial offset signal (ROFF) of the required amplitude. The radial position error signal continues to control the amplitude of the accelerating voltage in just the same manner as before by changing the phase of each of the phasors in opposite directions, keeping the resultant phase correct while changing its amplitude. One problem which might be anticipated in this procedure is that the cavity detuning for beam loading compensation will have to switch sign in the two groups of cavities at different times. Under heavy beam loading this may cause some transient problems.

At a typical beginning of the crossing period the required accelerating voltage is about 1.6 MV. If the synchronous phase angle is 55 degrees at that time the total rf voltage is 2 MV. Addition of the third harmonic increases the fundamental rf accelerating voltage requirement to 1.88 MV. This implies an increase of the synchronous phase angle to 70.6 degrees (π - 70.6 deg. for the jumped group). At this relative high phase angle the effective gain available to the radial position feedback loop is substantially decreased. Since a position error is expected to grow relatively slowly this is not a serious problem but it should probably be offset by the introduction of an increase in the anode program to increase the total rf amplitude during this period. Further mid-course corrections will be necessary so that the appropriate phase angle, accelerating voltage, and bucket shape can be established at the end of the crossing period.

In Appendix 5 an approximate analysis of the stability of the position feedback loop described is developed.

EXPERIMENTAL DATA, THE SIGNATURE

After all of this equipment is in place and operating, what does one look for? The improvement which is sought is, of course, a reduction in longitudinal emittance blow-up at transition, elimination of beam loss, and elimination of any effect from transition crossing on the transverse emittance of the beam. During the crossing period one would expect to observe a bunch broadening followed by narrowing on a mountain range display. Also spectrum analyzer signals should be displayed to look for microwave instability during crossing. The various parameters of the system such as starting time, relative amplitude of the harmonics and synchronous phase at start and end will be varied to study the beam response at varying intensity.