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3rd Harmonic RF Cavity for Transition Crossing in the Main Ring

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3rd Harmonic rf Cavity for Transition Crossing in the Main Ring

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Fermilab*

1 Introduction

Currently construction of high energy proton synchrotrons like MI at FNAL and MEB at SSCL has been planned, and in the long term these accelerators need to provide high intensity proton beams. One of the major problems encountered in similar accelerators in the past was related to the beam loss due to longitudinal emittance dilution resulting from various instabilities at transition crossing. The beam loss has been found to grow with beam intensity. The instabilities arise from Johnsen effect, Umstatter effect (related to space charge force), microwave instability etc.; in the past many cures have been suggested[1]. They were mainly γ_t-jump, continuous rf matching, artificial blow-up of the beam before transition to reduce space charge effect, etc. Out of these only γ_t-jump has been successfully tried and used in daily operation at CERN PS. In the 8.9 GeV Booster at Fermilab a similar γ_t-jump scheme has been implemented. For much larger rings the cost of a γ_t-jump system becomes prohibitive and also there is a possibility that it might introduce transverse beam emittance growth resulting from dispersion mismatch. Very recently a new scheme, RF HARMONIC scheme, has been proposed[2,3] for transition crossing . The feasiblity of this technique for MR has been examined in detail using the program ESME[4].

Figure 1 shows the basic principle of the rf harmonic scheme. Beam will be accelerated very near to the transition with the help of fundamental rf acceleration systems. A few msec before crossing the transition energy (where phase focussing starts disappearing), the rf phase is shifted to $\pi/2$ and at the same time the higher order harmonic system will also be turned on. The example shown in this figure is for a 2nd harmonic system added to the fundamental rf waveform. The voltages of both systems have to be adjusted so that every particle sees the same accelerating voltage as the synchronous particle. The shapes and relative amplitudes of combination of fundamental and higher harmonic voltage wave forms are shown in Figure 2. After crossing transition, the higher harmonic system is turned off, and the phase and amplitude of the fundamental rf system are set to the post-transition acceleration values.

This paper reports the present status and future plans of the implementation of the transition crossing RF harmonic system at Fermilab. The test is being carried out in the Main Ring (MR) which is used as a 150 GeV injector to the Tevatron.

2 An overview of the Transition Crossing rf system at FNAL

The MR at FNAL does not have a γ_t-jump scheme or any other scheme to reduce beam loss at transition crossing. Figure 3 gives a snap-shot plot of the beam loss at transition and bunch length oscillations during the cycle used for antiproton production in the MR. In this case about 6% to 7% beam loss at transition can be clearly seen. The data were taken for four Booster turns with 84 bunches. Studies made[5] with different initial beam intensities and longitudinal emittances showed that the beam loss increases exponentially with initial longitudinal emittance. The beam loss and the fractional emittance growth as a function of initial longitudinal emittance for two different intensities and rf voltages are shown in figures 4a and b. About 40% to 60% growth in bunch area is seen. These studies have shown that the MR is one place where we can test the new scheme for transition crossing. Besides, there is enough space in the MR at the F0 straight section to insert an additional rf cavity.

The implementation of the rf harmonic scheme in MR included development of 1) a 159 MHz rf cavity, 2) perpendicularly biased tuner, 3) power amplifier (PA) and 4) low level rf system and necessary software programs. All these were undertaken at Fermilab.

2.1 159 MHz rf cavity

We have considered two different options: a) design and fabricate an entirely new rf cavity or b) acquire an already existing cavity and modify it as per our needs. We chose the second option since it was adequate and less expensive. We have also considered using 2nd or 3rd harmonic RF system. Though the second harmonic rf system has about 35% more useful operating range as compared to a third harmonic rf system, it needs a new design for power amplifier which has to be operated at much higher power level. Also a 106 MHz rf cavity was not readily

Table I. A comparison of some of the properties of the CERN and the modified rf cavity.

Parameters	CERN rf cavity	With sleeves calculated*	Modified Cavity @
Accelerating Gap	26.9cm	11.22cm	10.922cm
Length (m)	0.748	0.748	0.748
fo(MHz)	195.456	159.804	159.08
Z (MOhm)	10.7	7.61	9.58**
$(\int E_z dz)$1/2	374 kV	374 kV	–
Q	51467	41443	37000
Transit time (sec)	.722	0.906	–
E_{max}(MV/m)	7.366	13.84	–
Power dissipated in Half cavity (Watt)	1.31E4	1.85E4	–
Stored Energy (Joule)	.55	.76	–

* Calculated using the SUPERFISH.
@ Measured without Tuner or PA loop on the cavity.
** This value is estimated by knowing power dissipation and voltage across gap. However the shunt impedance measured using the wire and bead pull measurements is systematically smaller[7].

available. On the other hand, it has been shown that a standard 100 kW Fermilab PA driven at the fundamental frequency of 53 MHz has the capability of delivering sufficient third harmonic current to excite the cavity to full amplitude. So, we proposed to buy a CERN LEP 200 MHz cavity and modify it to reduce the frequency to 159.09 MHz (which is 3.0*53.03 MHz).

In October 1991 a 197 MHz CERN LEP test cavity was obtained. The frequency of the cavity was reduced to 159 MHz by inserting two sleeves as shown in Fig. 5 (only a half section is shown in the figure). Table I gives a comparison of the calculated[6] and measured properties of the cavity. We have also made measurements[7] on the higher order modes of the cavity using two independent methods, namely stretched wire and bead pull. A network analyzer S_{21} spectrum from the cavity obtained using stretched wire is shown in figure 6. These results on higher order modes have been used later for experimental investigation of the coupled bunch instability.

2.2 Perpendicularly Biased Tuner

The momentum of the protons around transition energy of E_t =17.588 GeV in the MR follows approximately a parabola,

$$p(t) = (8.889 + 200 * t^2) GeV/c$$

with starting time of the ramp at t= 0.0 sec. Solving the above equation for t at transition energy we get the time for transition as t= 0.208sec after the ramp

Table II. Some Relevant Parameters for Cavity Tuner Development

Time (ms)	pc GeV	dpc/dt	γ*	β*	F0** (kHz)	V1 (MV)	V3 (kV)
193	16.3388	7.72E9	17.44	.9984	47.6366	1.858	240.7
208	17.5630	8.32E9	18.75	.9986	47.6462	2.003	259.4
223	18.8340	8.92E9	20.10	.9988	47.6557	2.147	278.1

* Relativistic quantities ** Revolution frequency

commences. Table II shows the details of machine parameters during 0.193sec to 0.223sec. From this we find that the total tuning required for the 3rd harmonic rf cavity is about 64.77 kHz. Since the fully loaded cavity has its Q more than 5000, the cavity has to be tuned dynamically during transition crossing. The minimum estimated time period required for non-focusing transition crossing is about 5msec in the MR. With enough safety margin the cavity is going to be turned on from about 15msec before the transition and turned off at about 15msec after the transition crossing. During this time the cavity has to be tuned electrically. In order to tune the cavity, an orthogonally biased Trans-Tech Iron-Yttrium-Garnet ferrite tuner system has been built. This is a high frequency and low loss ferrite. Figure 7 shows the final design of the 3rd Harmonic RF cavity tuner[8] built using G510 ferrite. The loop area required for coupling the magnetic field energy is about 54cm^2.

Before the final selection of the G510 we have made fairly detailed studies[8] on ferrite G810 and G510 from two different batches. We find that G510 ferrites obtained from two different batches show significant differences. As a result of this we could not mix two ferrite rings from the two different batches to have slightly more operating range. However, we finally decided to use three G510 ferrite rings from the same batch which had identical properties and also give sufficient operating range.

Figures 8a and 8b show frequency and Q responses of the cavity with power amplifier coupling loop and tuner loaded. The small difference between the frequency range in the figure 8b and that actually required at transition energy can be adjusted using a mechanical tuning system attached to the cavity. Assuming a maximum allowable power dissipation not more than 0.5 W/cc/acceleration cycle, the total Q change is estimated to be about 2000, which gives a tuning range of more than 62 kHz. Thus the necessary tuning range has been achieved with the present tuner. In the present design of the tuner, options have also been made to insert additional ferrite rings if necessary in future.

2.3 Power Amplifier

Figure 9 shows the third harmonic rf cavity power amplifier developed at Fermilab[9]. This is built using EIMAC 4CW25000B tetrode and has a 0.616λ long anode resonator. The PA is found to provide a gap voltage better than 274 kV at 159 MHz with a power better than 9.2 kW.

3 Tests with Beam-on Conditions in the MR

Figure 10 shows the third harmonic RF cavity in the F0 straight sector of the MR tunnel with the PA and the tuner mounted on the cavity. Figures 11a and 11b show beam-on conditions. During these measurements we had 0.70 to 1.3E12 protons/84 bunches in the MR beam. Any noticeable coupled bunch instabilities those would arise from the excitation of the higher order modes in the third harmonic cavity have not been seen.

Now we are in the process of testing the automated program and low level RF system specifically built for the 3rd harmonic rf system. In future, studies will be made using dedicated cycle in the MR. We are planning to blowup the longitudinal emittance and study the effect of the cavity on the beam loss and the emittance dilution as a function of beam intensity. This scheme will be implemented in the regular operation of the MR after a successful testing.

Recently the longitudinal emittance of the Fermilab Booster beam has been improved by a factor of more than four (ϵ_l has now been reduced from .2 eV-sec to .05 eV-sec). This qualitatively suggested that the same 3rd harmonic RF system can be used in the Main Injector. The detailed study is underway. If needed, building a new 2nd harmonic rf cavity (which has larger operating range) will be considered.

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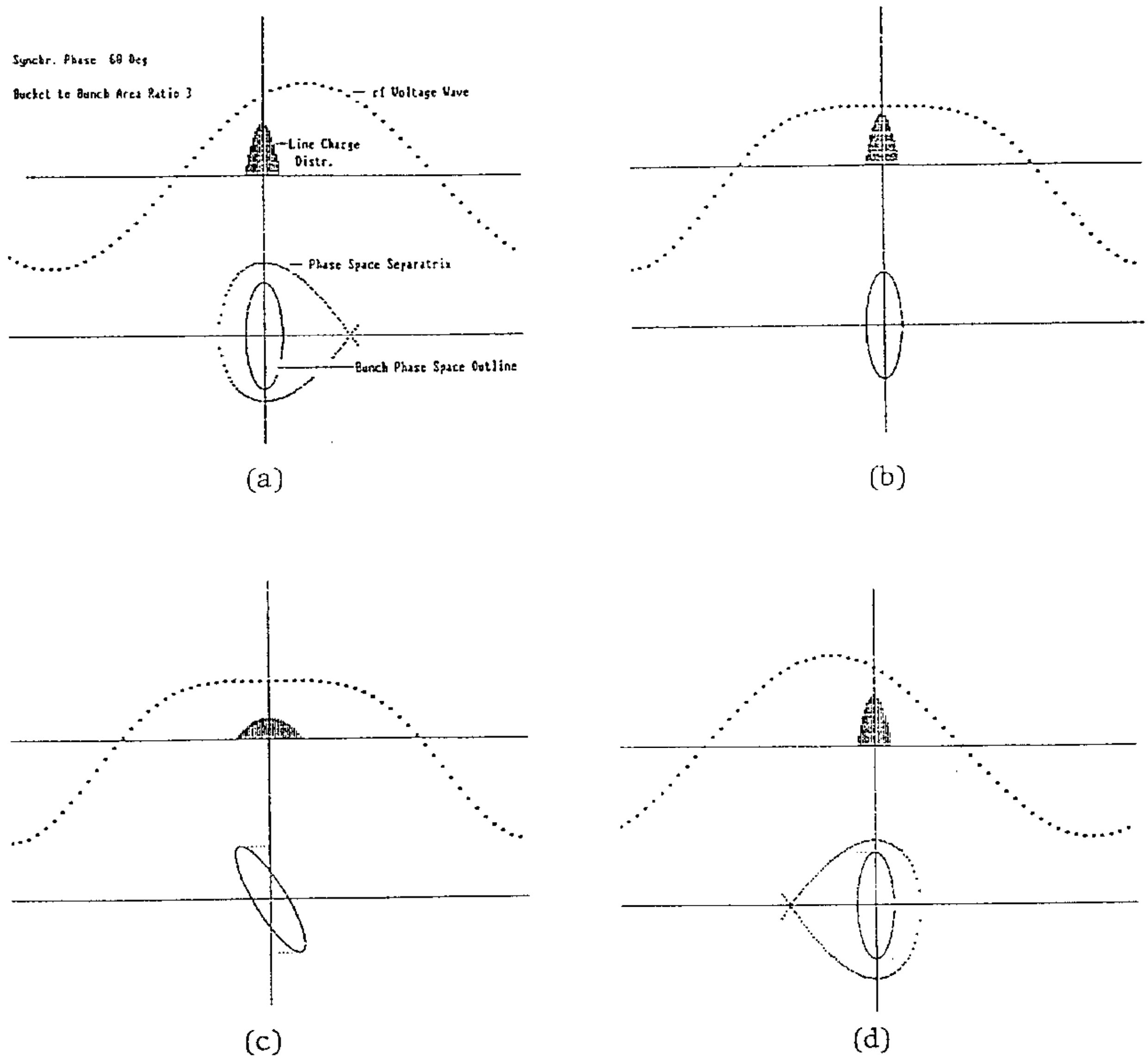
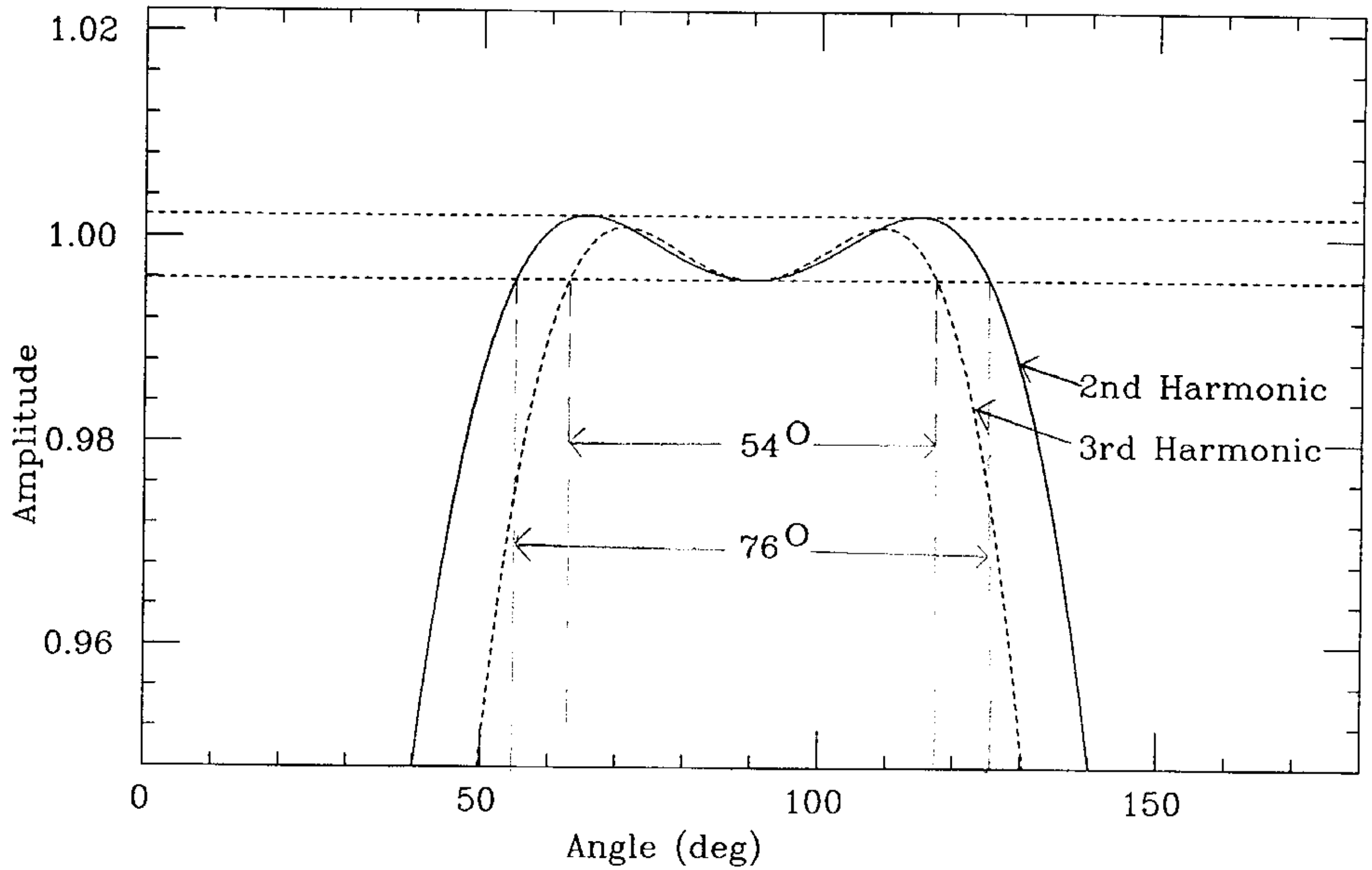


Fig. 1. Principle of transition crossing with second harmonic system. RF voltage wave, phase space contour,moving bucket and line charge distribution for a)prior to transition with synchronous phase angle 60°, b) with rf voltage shifted to 90° and second harmonic added at a phase of 270°, c) same beam representations at transition time d) a few milliseconds after the transition with second harmonic system off also fundamental rf phase shifted to a post transition acceleration phase. Very near to the transition the rf bucket height becomes too large to show.



sin(wt) + .275*cos (2wt)

sin(wt) + .1295*sin (3wt)

Fig. 2. Combined voltage wave forms of fundamental and second (solid line) and third (dashed line) harmonics with phases as shown above.

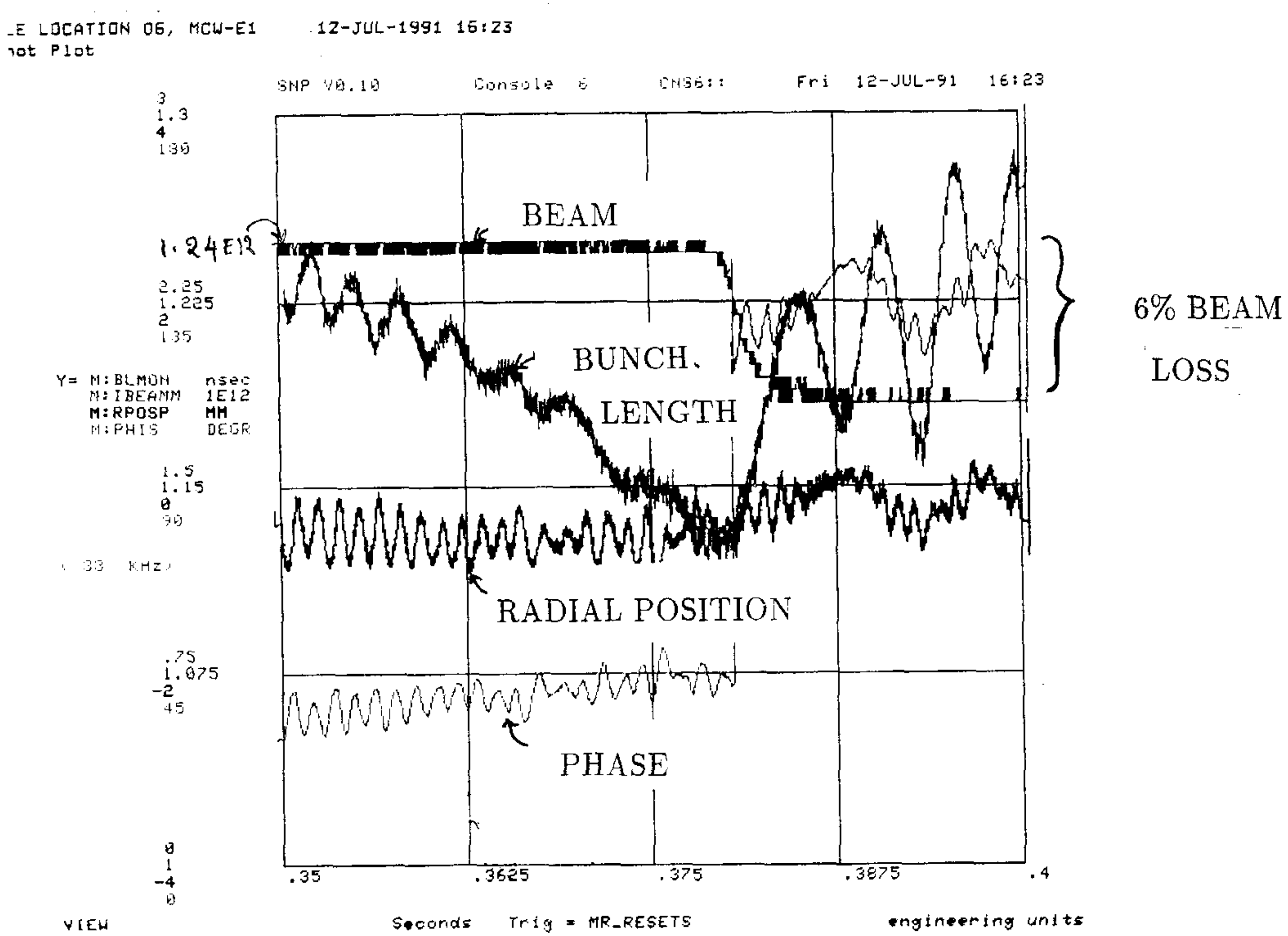
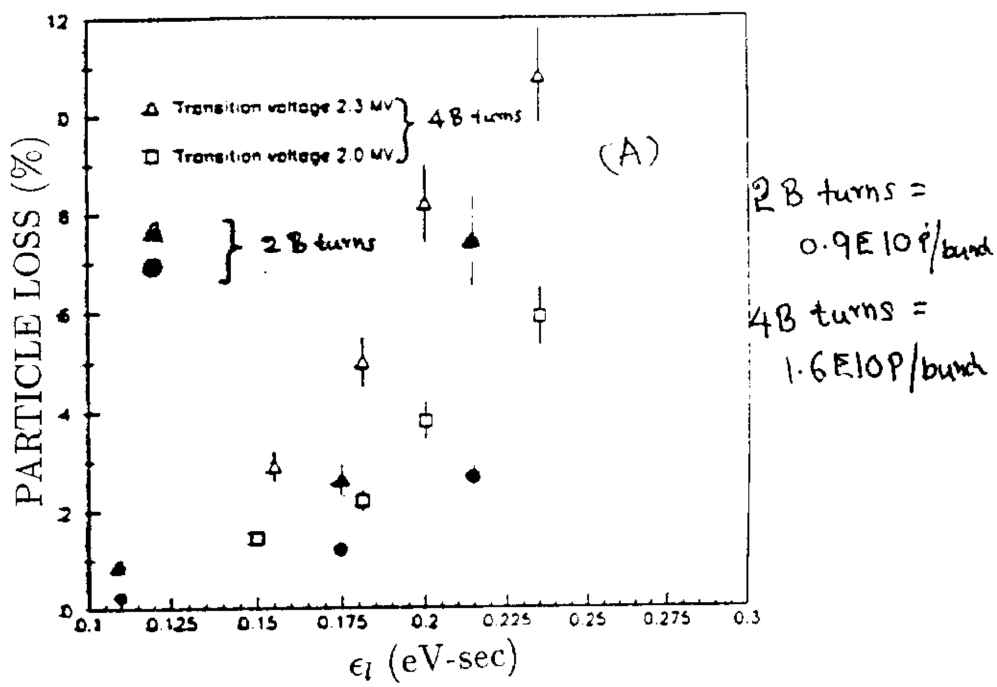


Fig. 3. Present condition of Main Ring Beam at FNAL during transition Crossing. About 6% beam loss can be clearly seen. Phase jump, radial position and bunch length oscillation near transition are also shown.

BEAM LOSS VS ϵ_l



FRACTIONAL EMITTANCE GROWTH VS ϵ_l

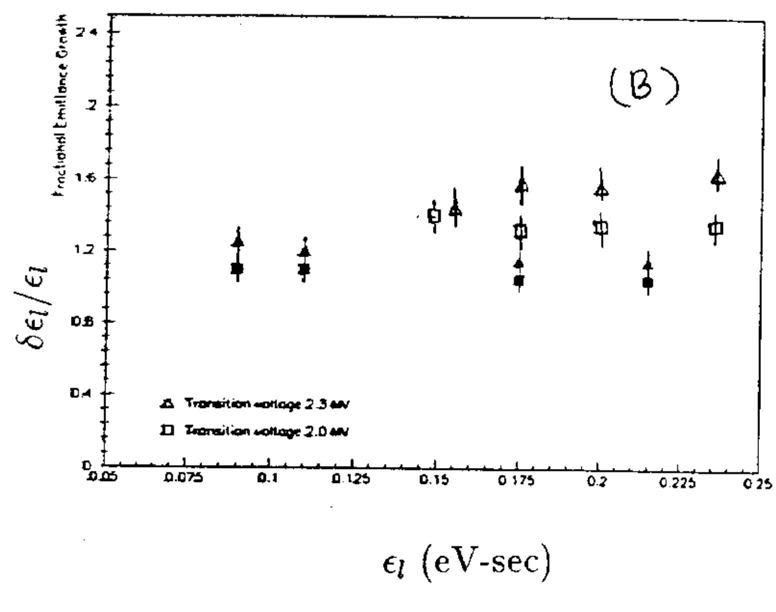


Fig. 4. An experimental study of a) beam loss and b) longitudinal emittance growth in the Main Ring near transition crossing for two different initial beam intensities.

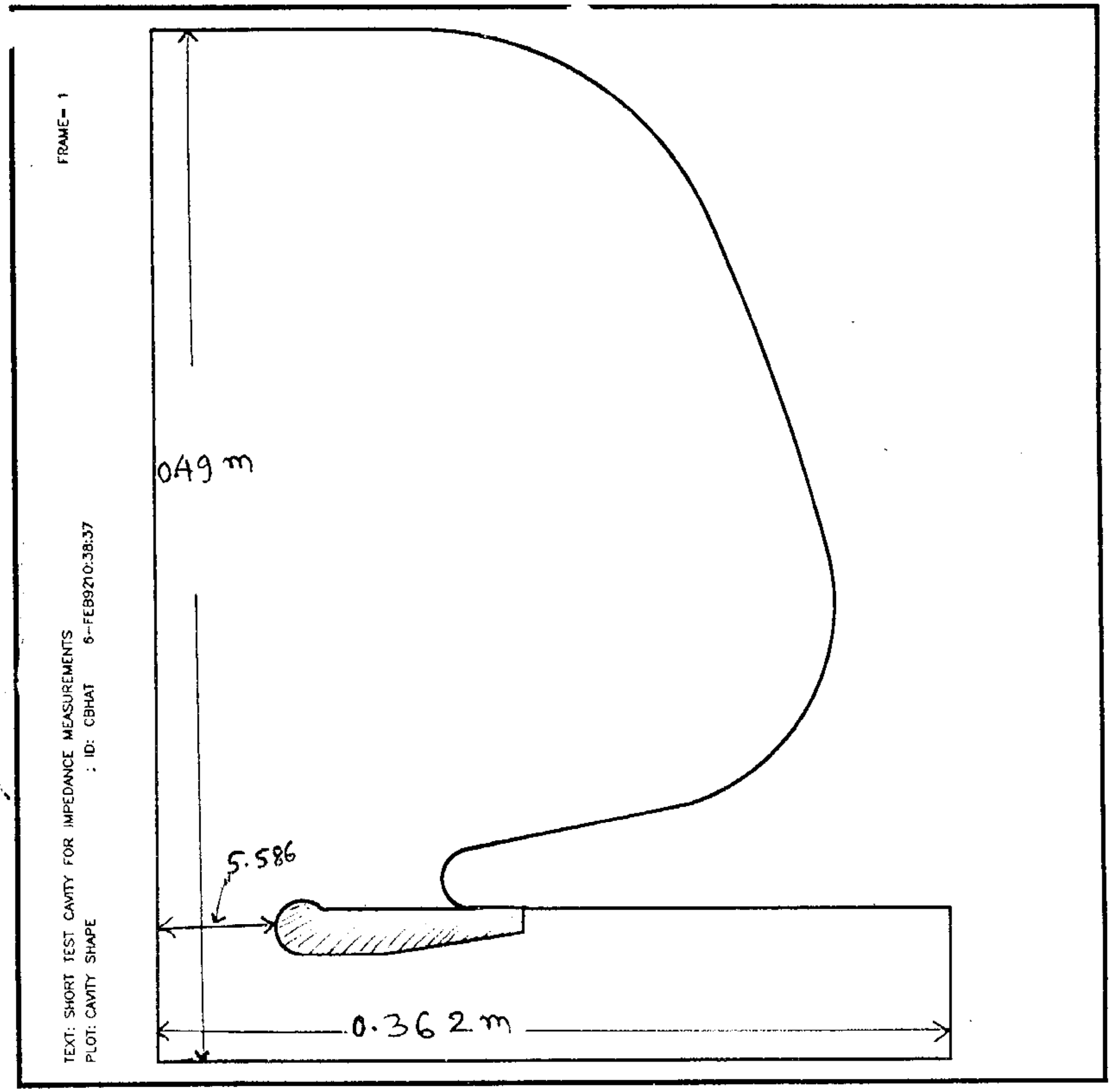


Fig. 5. CERN rf cavity tuned to 159MHz by inserting a sleeve.

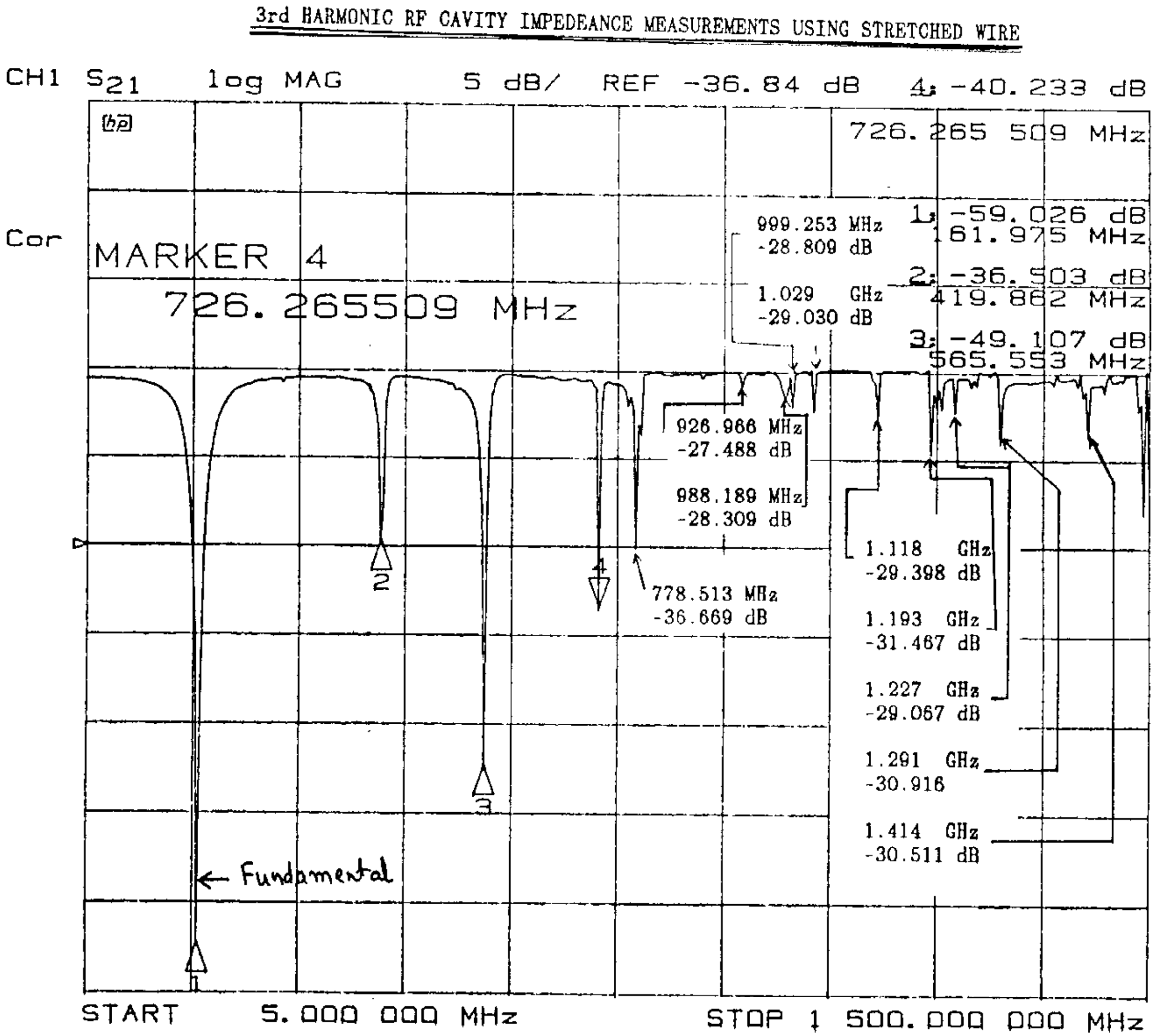


Fig. 6. Higher ordered modes in the 159MHz modified CERN rf cavity. Network analyzer S21 measurements made using impedance matched (50Ohm) stretched wire.

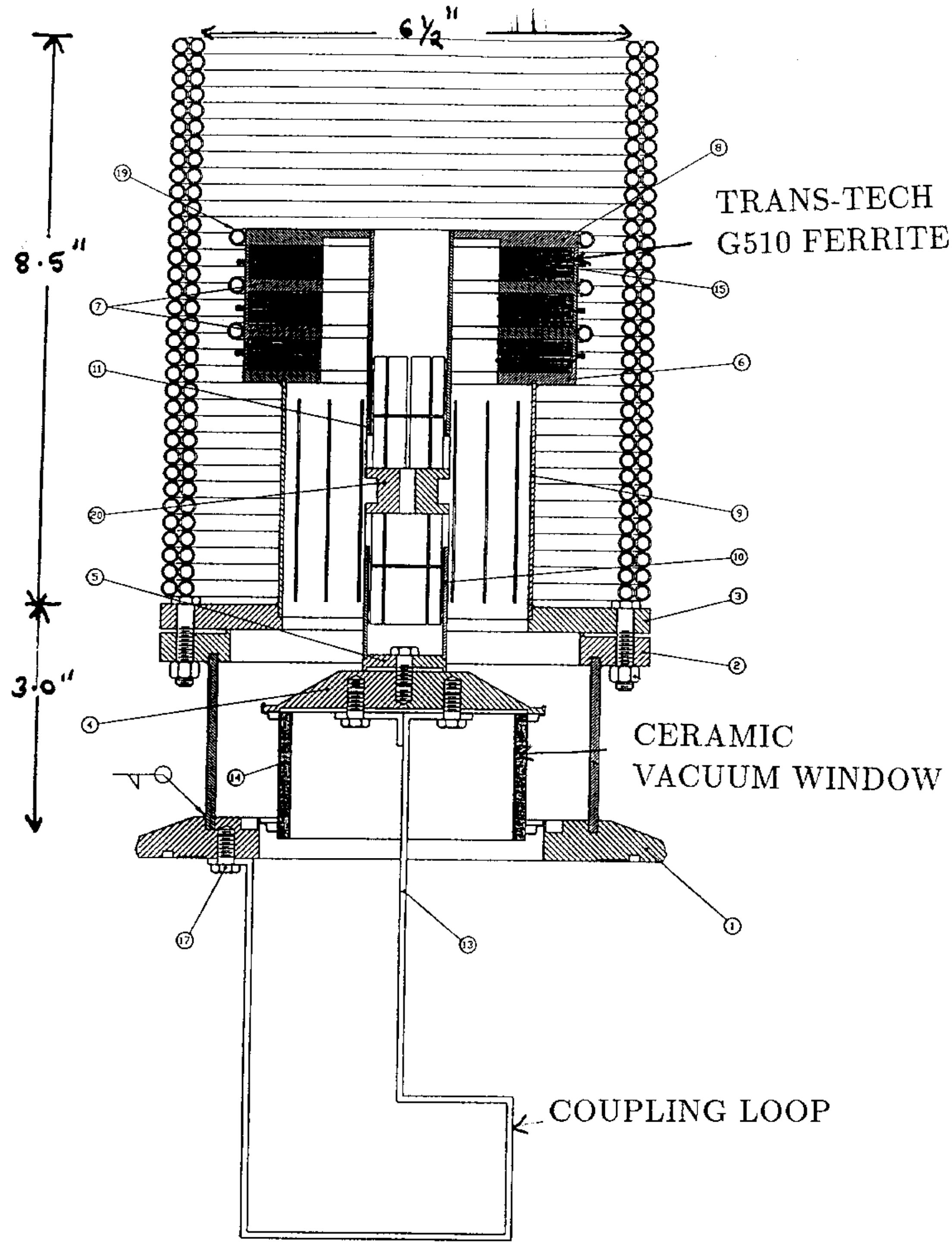
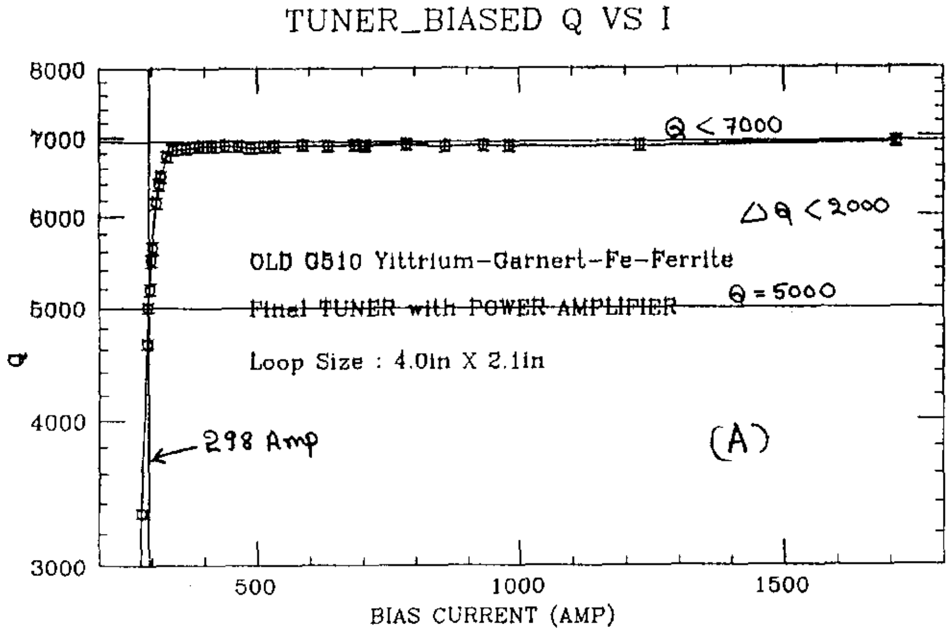
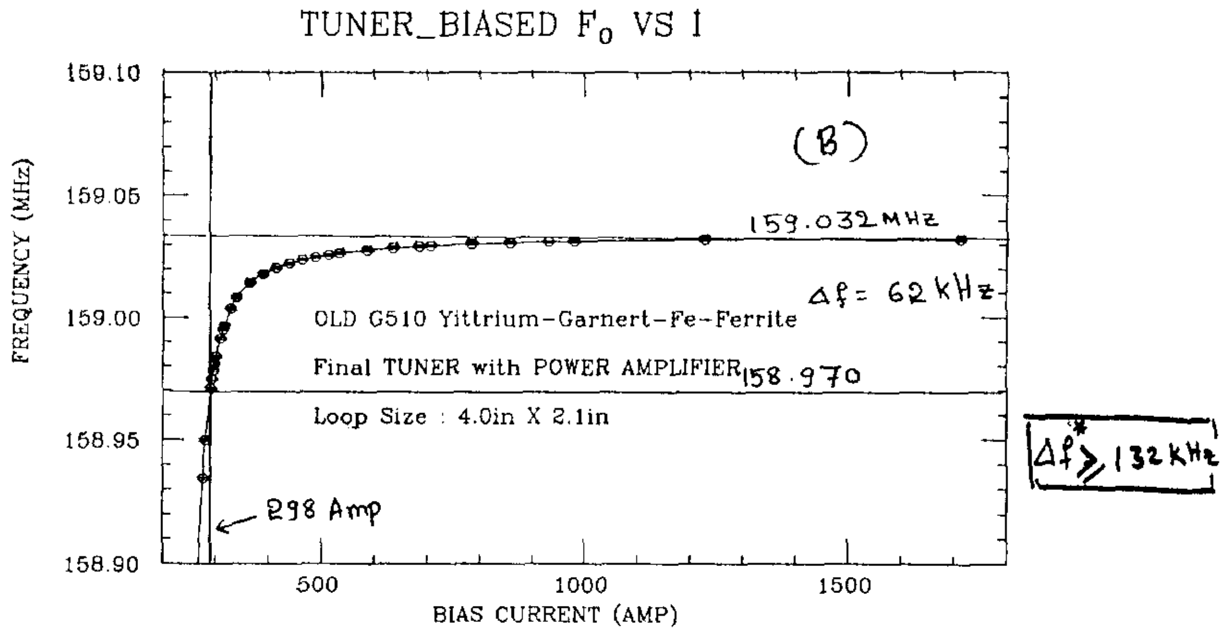


Fig. 7. A perpendicularly biased TRANS-TECH G510 yttrium-garnet-iron- ferrite tuner for third harmonic rf cavity at FNAL.



Data is taken on 2/17/92. Pts. below 250amp not showned



Data is taken on 2/17/92. Pts. below 250amp not showned

Fig. 8. Frequency and Q responses of the 159MHz rf cavity a function of tuner bias current. During these measurements the cavity was not under vacuum.

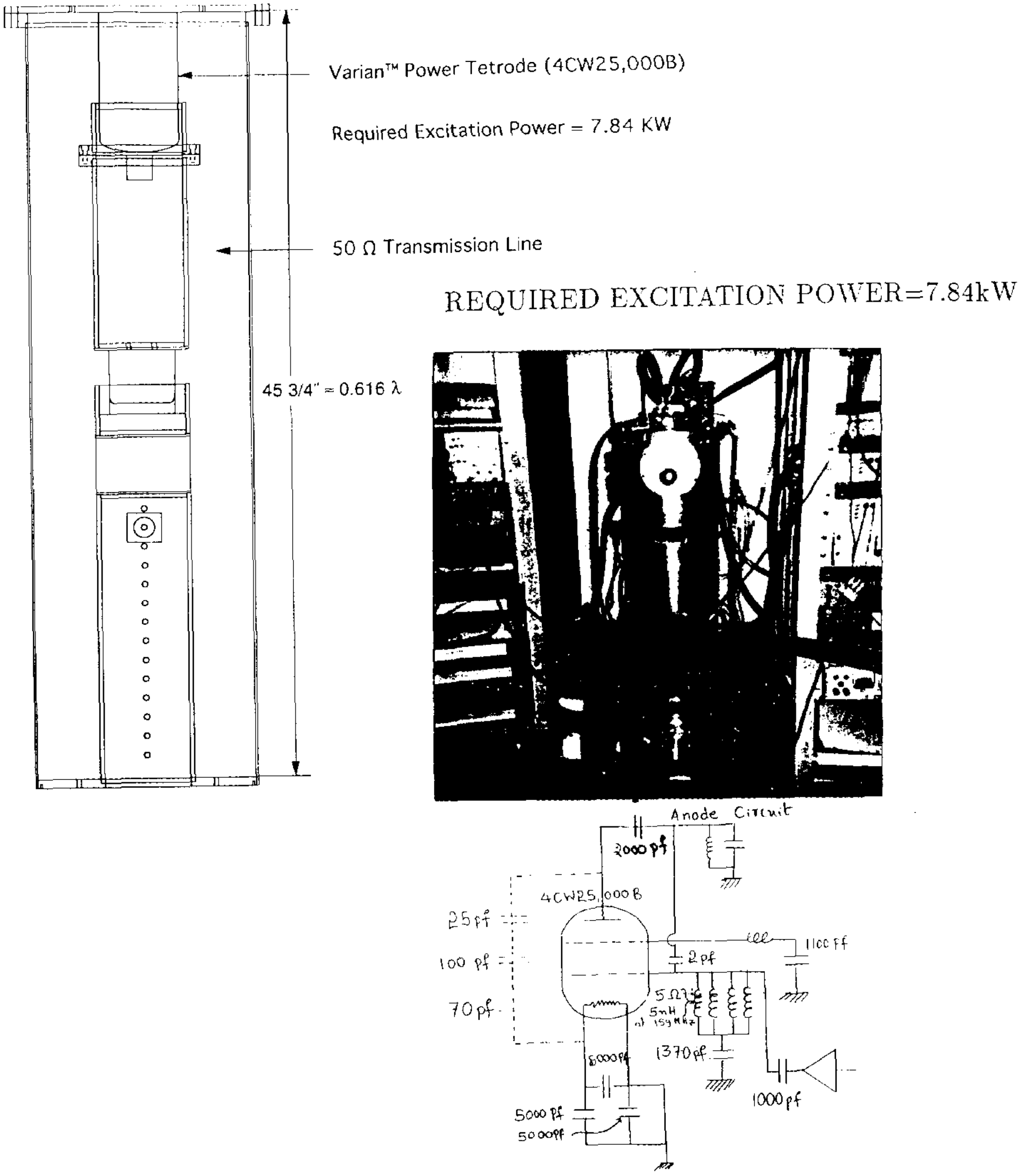


Fig. 9. Third harmonic rf cavity power amplifier (PA) system. a) design b) picture of a built module and c) equivalent circuit. (J. Dey and D. Wildman).

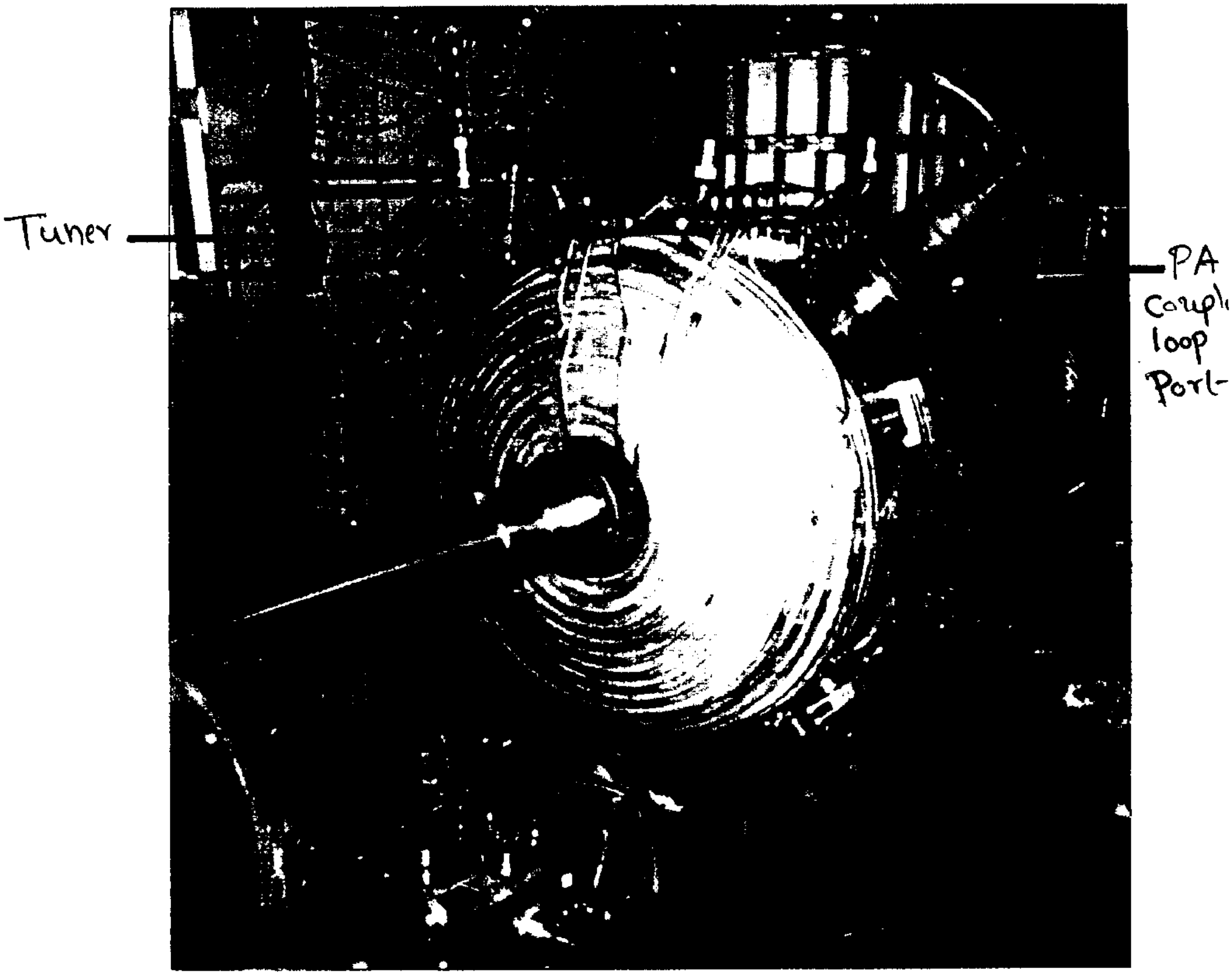


Fig. 10. Third harmonic rf cavity in the Main Ring F0 straight section. Tuner solenoid and PA coupling loop connection can be seen.

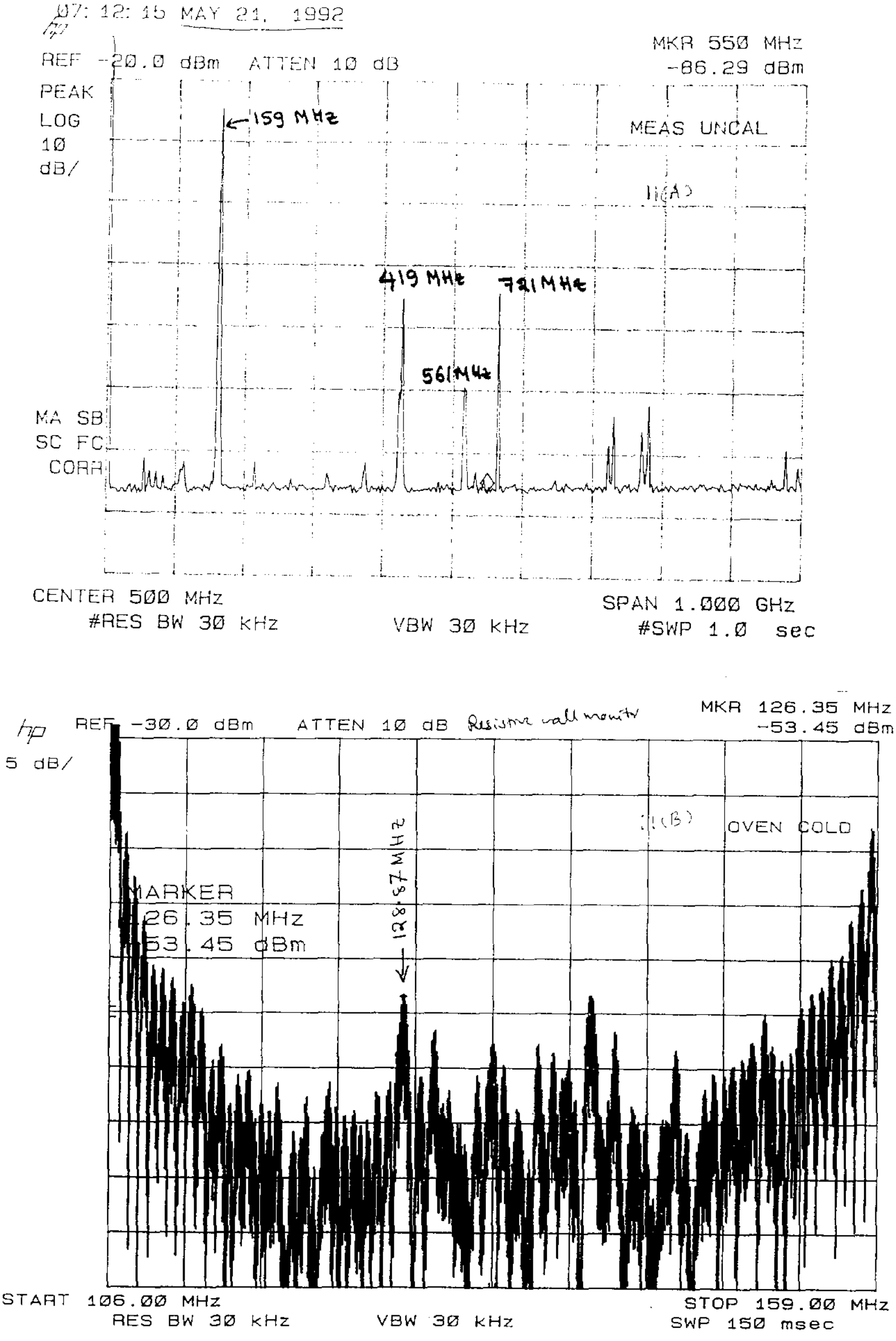


Fig. 11. Beam on measurements on the third harmonic rf cavity with spectrum analyzer. a) The beam spectrum taken with 0.7E12 protons/84bunches at 29 cycle. b) A measurement on coupled bunch instability with about 1E12 p/84 bunches.