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Further Progress in Commissioning the Very High Frequency (VHF) Cavity

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Reported by K. Reece and L. Ahrens

Subject Further Progress in Commissioning the Very High Frequency (VHF) Cavity

Summary

The effects of powering the VHF cavity on a 3.5 GeV front porch have been experimentally investigated. With a swept phase modulation program, stable dilution and nearly lossless transition crossing was achieved with 1.5×10^{13} protons delivered to the HEP program. The Kats[1] prescription for dilution parameters works well. Some additional dilution phenomena have been encountered.

Background

As previously reported in AGS Studies Report No. 252,[2] the Very High Frequency (VHF) rf cavity located in the G-20 straight section of the AGS has produced in a reproducible manner approximately a factor of two increase in longitudinal bunch area. This work was conducted using a 1.5 GeV (kinetic) front porch on the AGS main magnet power supply cycle. It was noted during these studies, however, that the beam rotation frequency on this porch was near that required to drive a longitudinal beam instability (AGS Studies Report No. 251[3]). Another difficulty of operating at this energy was that circulating beam was lost at a constant rate for the duration of the front porch. This loss appeared to be correctable by adjusting the stopband correction elements in the AGS. Since, however, the stopband corrections are not routinely available to operate in a programmed fashion (different values at different momenta), the loss was a fact of life on the 1.5 GeV front porch.

Procedure

It was decided to move the operating energy for the VHF cavity to 3.5 GeV (kinetic) to try to avoid the problems just outlined and to provide slightly more longitudinal phase space area in the moving bucket after dilution. At 3.5 GeV, there was no indication of either a longitudinal instability or a beam loss attributable to stopbands in the AGS. The primary effort of the present study was to quantify the amount of longitudinal dilution as a function of the fixed frequency of phase modulation of the VHF cavity rf. First, though, a swept phase modulation program was tried. This was simply the program found in the 1.5 GeV work to yield most efficient dilution scaled by the ratio of the beam synchrotron frequencies at the two energies. The frequency of phase modulation and the sweep period were both scaled down by this amount. The operating parameters are listed in Table I.

Table I
Operating Parameters

f_{vhf}/f_{rf}	21-1/3
Cavity Frequency	92.939 MHz
Cavity Voltage	19 kV
Main RF Accelerating Frequency	4.3565 MHz
Main RF Accelerating Voltage	161 kV
Frequency of Phase Modulation	2.17-2.53 kHz
Phase Modulation Sweep Period	11 ms
Phase Deviation	$\pm\ \pi$
Dilution Period	100 ms

Table I'

Menu Option Displays from the VHF_CONTROL Program.

CANCEL | HELP

$n-\frac{f_{vhf}}{f_{rev}}$	$\frac{f_{vhf}}{f_{rf}}$	f_{rf}(MHz)	p(GeV/c)	Gauss clock
270	22 6/12	4.131	2.314	4453
269	22 5/12	4.146	2.377	4578
268	22 4/12	4.161	2.446	4713
267	22 3/12	4.177	2.520	4859
266	22 2/12	4.193	2.601	5020
265	22 1/12	4.209	2.690	5196
264	22	4.225	2.789	5391
263	21 11/12	4.241	2.899	5608
262	21 10/12	4.257	3.022	5852
261	21 9/12	4.273	3.162	6128
260	21 8/12	4.290	3.323	6446
259	21 7/12	4.306	3.511	6817
258	21 6/12	4.323	3.734	7257
257	21 5/12	4.340	4.003	7790
256	**21 4/12**	**4.357**	**4.340**	**8455**
255	21 3/12	4.374	4.777	9318
254	21 2/12	4.391	5.377	10504
253	21 1/12	4.408	6.277	12280
252	21	4.426	7.851	15391
251	20 11/12	4.443	11.871	23333

RETURN | GRAPH | SAVE | HELP

DILUTION ARCHIVE FILENAME: STUDY

DILUTION NUMBER 4 | SWITCH: OFF

*** TIMING ***

TP0 (GC): 8000 TP1 (GC): 8260 TP2 (GC): 8464

TP3 (ms): 50 TP4 (ms): 110 TP5 (ms): 140

TP6 (GC): 10000 RF OFF (ms): 100

*** PHASE MODULATION ***

FREQ PROG: ⁄\⁄\⁄\⁄\ SWEEP FUNC: linear

MODE: CONTINUOUS SWEEP AND RESET

FREQ START(kHz): 2.17 FREQ STOP (kHz): 2.53

PHASE DEV (v): 3.60 SWEEP TIME (ms): 11

AGS/VHF RF PHASE OFFSET (deg): 0

DRIVE LEVEL AMPLITUDE (kv): 0.00

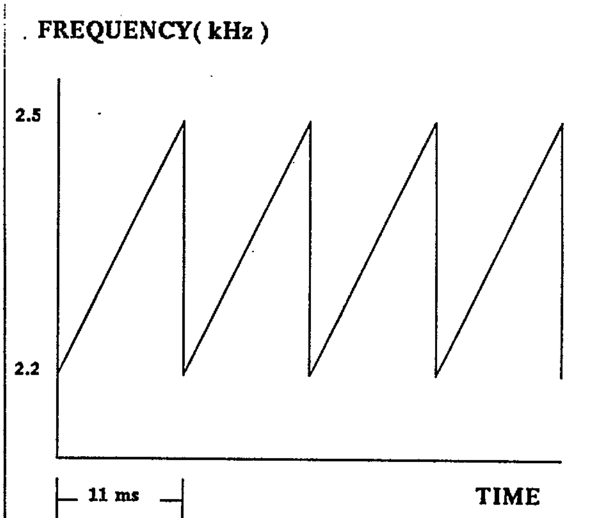
FREQ DIVIDER SELECT => 256 REF FREQ: 92.9400

SYNCHRO LOCK: OFF

DILUTION SETUP FILENAME: STUDY

CREATION DATE: Thu Apr 6 09:53:46 1989
COMMENTS: working file for commissioning.

DILUTION NO.	1	2	3	4	5
SWITCH	off	off	off	off	off
TIMING					
TP0	3500	6000	7100	8000	41500
TP1	4460	6210	7250	8260	41750
TP2	4548	6230	7500	8464	42000
TP3	65	2	2	50	2
TP4	50	2	2	110	4
TP5	60	2	2	140	6
TP6	4800	7000	7900	10000	48000
RF OFF	40	2	2	100	40
PHASE MODULATION					
FREQ PROG	triangle	sine	sine	triangle	triangle
SWEEP FUNC	linear	sine	linear	linear	linear
MODE	cont/res	cont/res	cont/res	cont/res	cont/res
FREQ START	6.00	2.00	2.00	2.17	6.00
FREQ STOP	7.00	9.00	9.00	2.53	7.00
PHASE DEV	3.60	5.00	5.00	3.60	5.00
SWEEP TIME	4	4	4	11	4
PHASE OFFSET	250	0	1	0	0
DRIVE LEVEL	100.00	112.00	112.00	0.00	0.00
FREQ DIVIDER	270	296	272	256	251
SYNCHRO LOCK	off	off	off	off	off



The beam synchrotron frequency measured on the front porch with full main rf voltage was used to derive that rf voltage. Earlier calibrations had shown that the rf voltage program function generator amplitude was linear with actual rf voltage applied to the gaps. Therefore, the rf voltage at different setpoints was derived from the function generator amplitude, not from direct measurement.

As detailed in the previous studies report,[2] an AGS main magnet front porch of 200 ms length was achieved and the beam rf frequency measured. The operating frequency of the VHF cavity was then derived and set. Also, the main rf accelerating voltage was lowered to 160 kV/turn.

Observations and Results

Beginning with the swept phase modulation program scaled by synchrotron frequency and reduced voltage on the main rf system, the dilution as seen on the F-20 wall current monitor was significant (Figure 1). The reduction at peak bunch amplitude (qualitative measure of dilution using this diagnostic) was most pronounced with lower rf gap voltage applied to the main rf system. As this voltage was increased (the ratio of V_{vhf}/V_{rf} decreased), the amount of dilution decreased (Figure 2). The variation of another possible dilution parameter; namely, the absolute setting of the VHF cavity voltage was not explored.

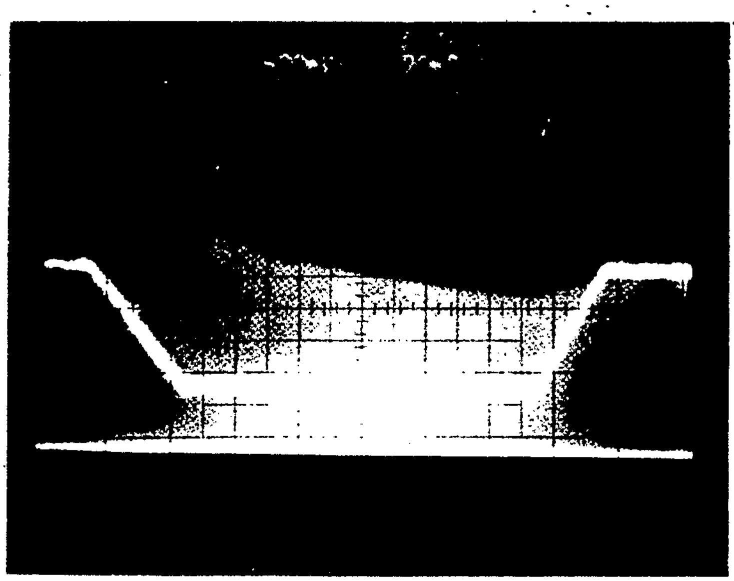


Figure 1. F-20 wide band current transformer envelope and main accelerating rf voltage (20 ms/large div.).

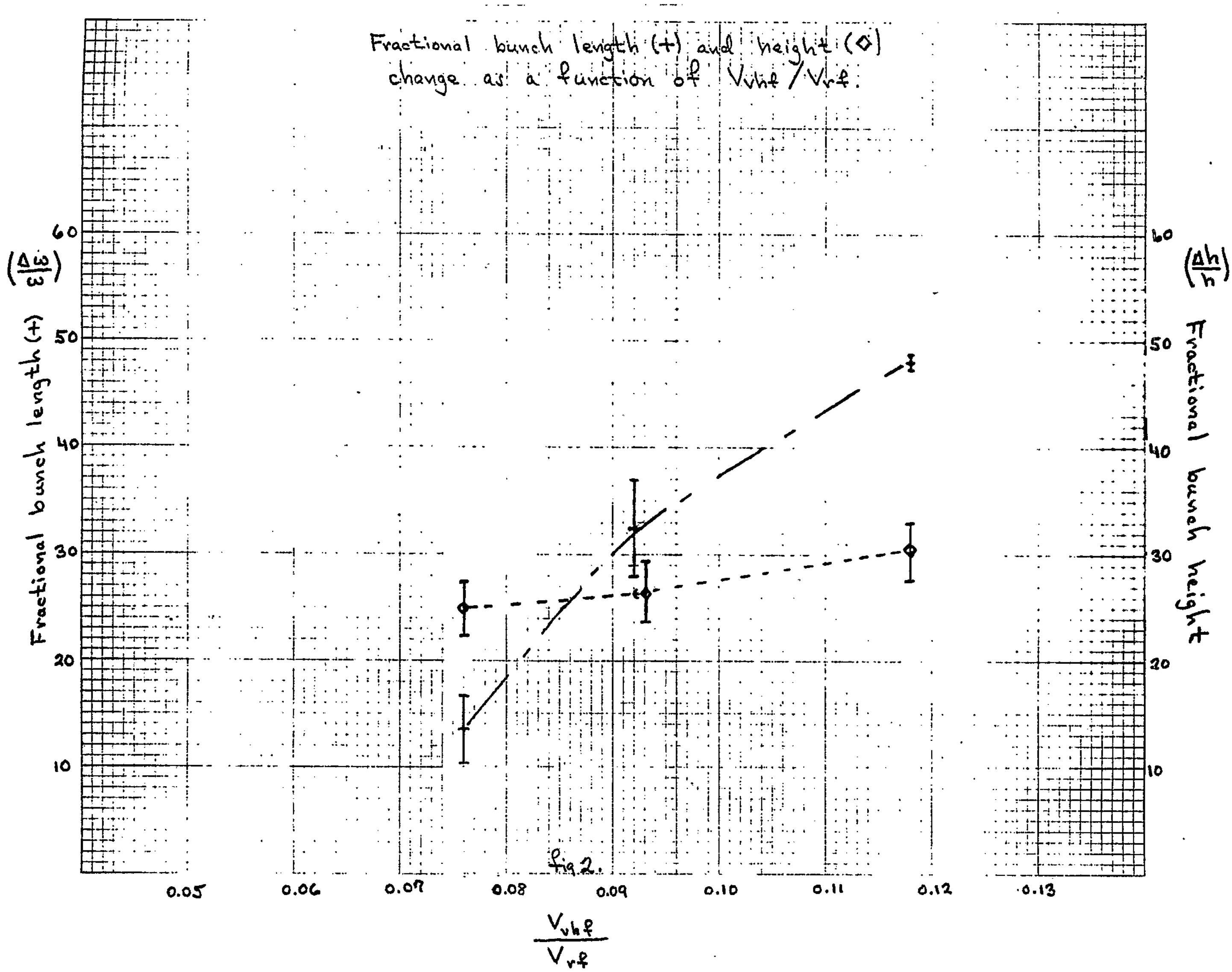
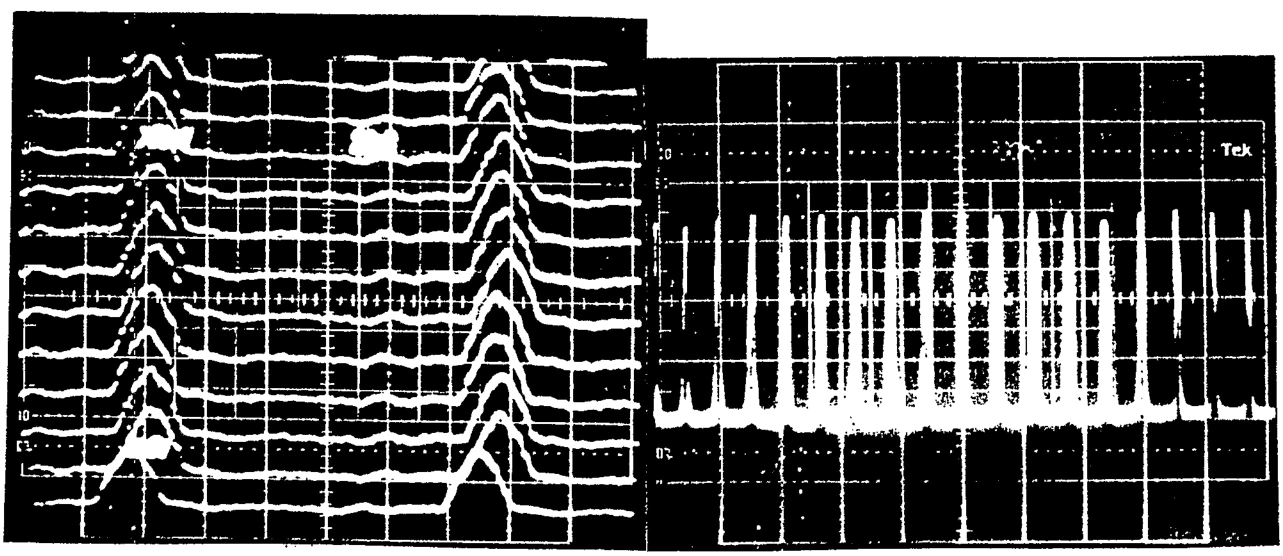


Figure 2. Fractional bunch length (+) and height (◇) change as a function of V_{vhf}/V_{rf}.

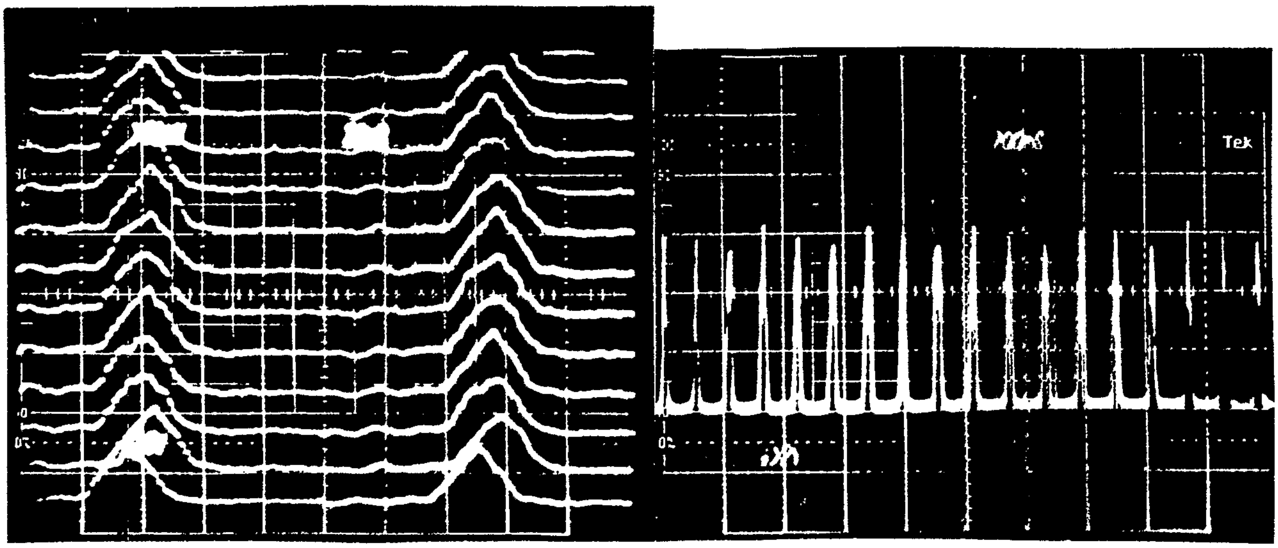
An unambiguous definition of the "best dilution" has still not been obtained except to say that the final "measure" of this quantity should probably be the transition efficiency in the AGS as a function of VHF cavity operating characteristics. With this in mind, the bunch length and peak amplitude changes were documented as the cavity parameters were varied.

First, though, a phenomenon was noted with the main rf voltage at normal (full) value and the VHF cavity powered, namely, a periodic variation in the amount of dilution the twelve bunches experienced. As can be seen from wall current monitor displays, there is a uniform, uncorrelated distribution in bunch lengths and peak amplitudes with the cavity off (Figure 3). But when the VHF cavity is turned on (Figure 4), there is a definite periodic structure most pronounced in the peak amplitude measurement that repeats every three bunches. This phenomenon is much less apparent with a reduced setpoint for the main rf voltage. Since we are working at a dilution cavity frequency which is 21-1/3 times the main rf accelerating frequency, the relative phase of the dilution cavity rf and the bunch repeats for every third bunch so in that sense the phenomenon is certainly possible. One might expect with all the sweeping it would wash out and, indeed, with lower accelerating gap volts, it did.



(a) (b)

Figure 3. F-20 wide band current transformer with VHF cavity OFF, showing: (a) successive bunches per trace (20 ns/small div.), and (b) contiguous bunches (200 ns/small div.).



(a) (b)

Figure 4. F-20 wide band current transformer with VHF cavity ON, showing (a) successive bunches per trace (20 ns/small div.), and (b) contiguous bunches (200 ns/small div.)

A fixed frequency phase modulation program scan was done from 1.0 kHz to 5.0 kHz in 500 Hz steps. Then 250 Hz steps were taken in the region near the observed maximum dilution point (which was also quite close to the center of the original scaled swept frequency program). From the bunch distributions (Figure 5), there appears to be a very fine dependence on the VHF phase modulation frequency. Upon close examination, the bunch length increase may be significant but the peak amplitude decrease is small due to a central peak with long tails. For certain frequencies, the variation in bunch height over several pulses was large as the bunch distributions changed from rather Gaussian to very "peaked" in nature (Figure 6).

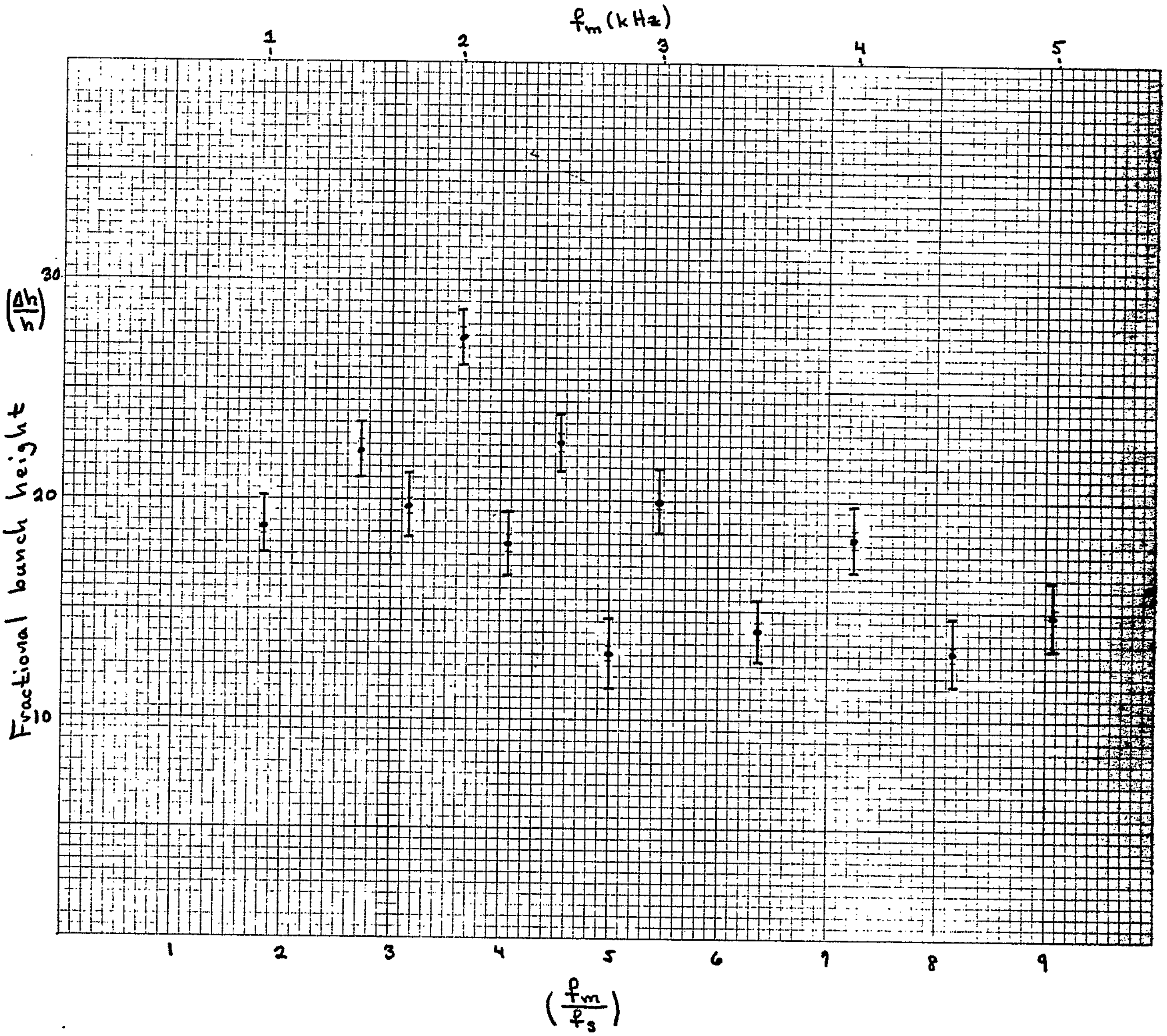


Figure 5. Fractional bunch height (Δh/h) as a function of phase modulation frequency (top scale) and normalized by synchrotron frequency (bottom scale).

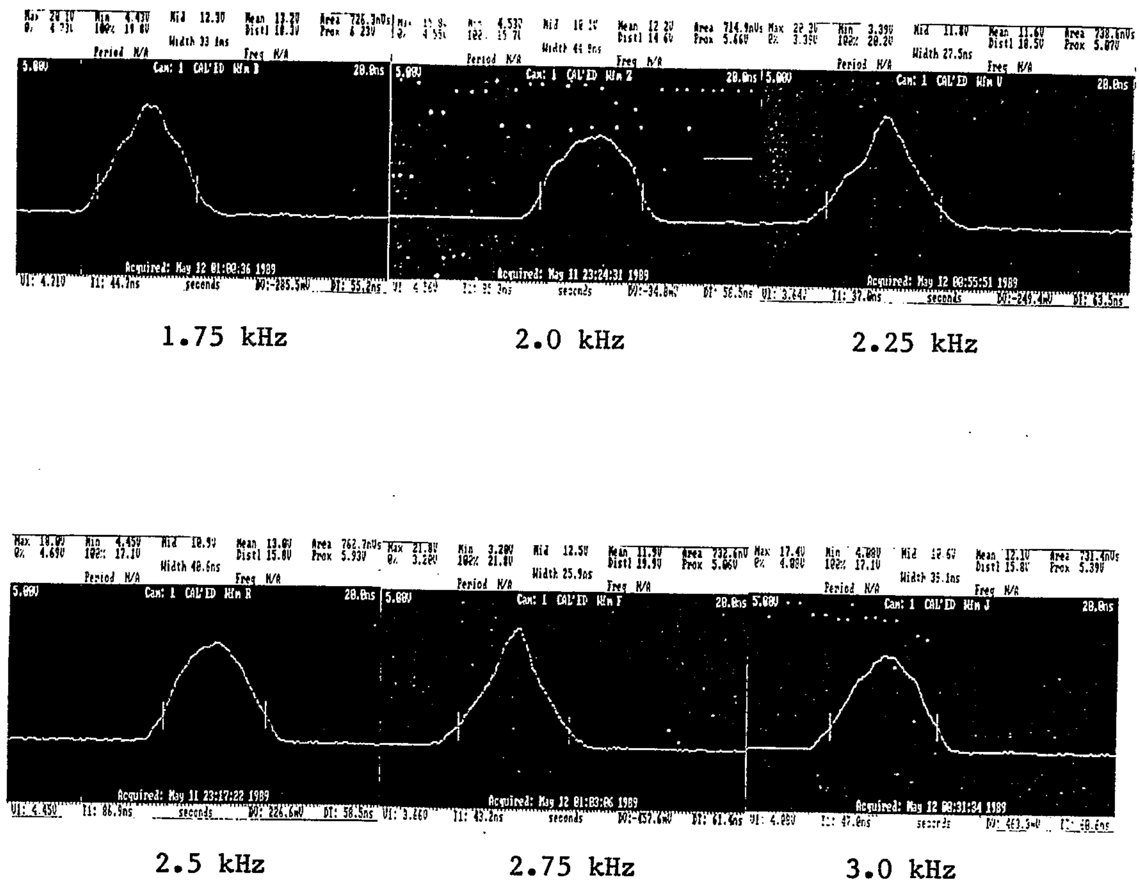


Figure 6. Individual buncher distributions with the VHF cavity powered and modulated by a fixed frequency program.

The bunch length, however, varied smoothly as a function of phase modulation frequency (Figure 7). Both measures give a maximum in the region of 2.0–2.25 kHz which is near the central frequency of the scaled swept modulation frequency program suggested by the earlier measurements.[1,2]

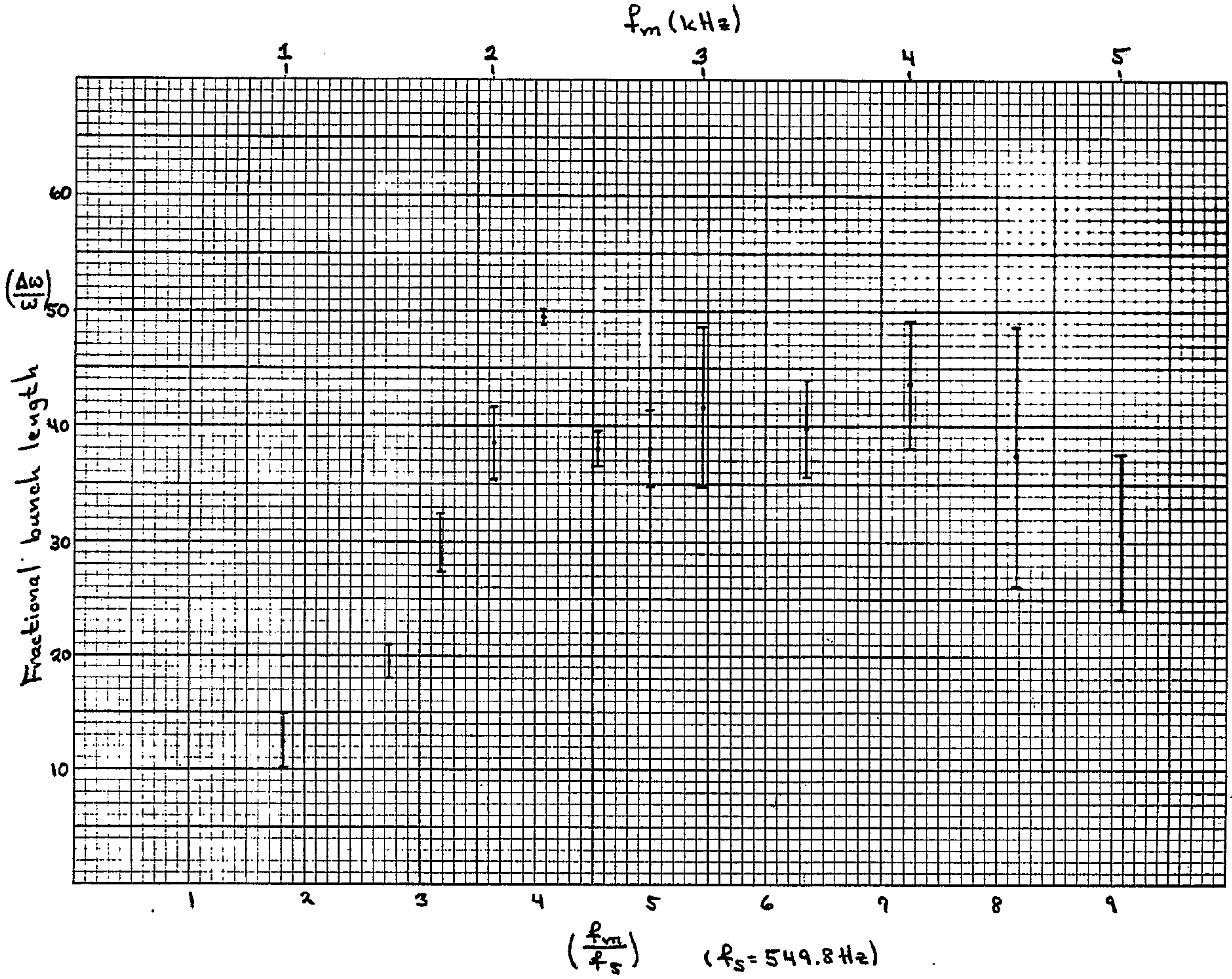
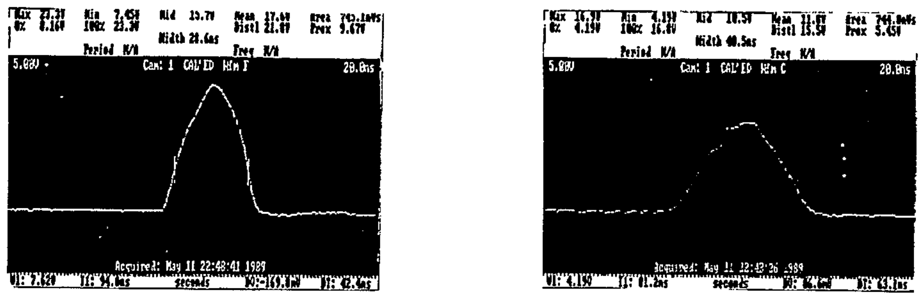


Figure 7. Fractional bunch length (Δw/w) as a function of phase modulation frequency (top scale) and normalized by synchrotron frequency (bottom scale).

The VHF cavity parameters were returned to the original swept function set (see Table I), and representative bunch shape measurements were acquired at the end of the flattop with the cavity off and on (Figure 8).



(a) (b)

Figure 8. Typical AGS bunch distribution as measured at the end of the dilution front porch with the VHF cavity (a) ON and (b) OFF.

The bunch area can be calculated[4] from the following equation

$$A_{bunch} = 16 \left[\frac{eV R^2 E_s}{2\pi h^3 c^2 \eta}\right]^{1/2} \frac{\pi}{64} \Delta^2 \left(1 - \frac{5}{384} \Delta^2\right)$$

Δ = bunch length (radians) (including 95% of the particles)

$h = 12$

$c = 2.998 \times 10^8$ m/s

$R = 128.457$ m

$E_s = E_o + T = 4.438$ GeV

$\eta = \frac{1}{\gamma^2} - \frac{1}{\gamma_{tr}^2} = 0.0316$

$eV = 161$ keV

$$\rightarrow A_{bunch} = 0.4858 \, \Delta^2 \left(1 - \frac{5}{384} \Delta^2\right)$$

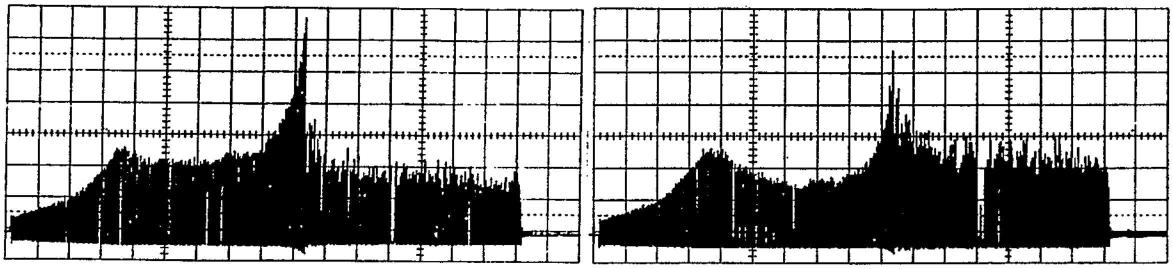
Table II

Bunch Area as a Function of Phase Modulation Program

f_m	A_b(eV-s)
0.0	$0.658 \pm 3.6 \times 10^{-6}$
1.0	$0.830 \pm 5 \times 10^{-4}$
1.5	$0.931 \pm 2 \times 10^{-4}$
1.75	$1.103 \pm 5 \times 10^{-4}$
2.0	$1.240 \pm 8 \times 10^{-4}$
2.25	$1.436 \pm 1 \times 10^{-4}$
2.5	$1.233 \pm 2 \times 10^{-4}$
2.75	$1.233 \pm 8 \times 10^{-4}$
3.0	$1.30 \pm 3.5 \times 10^{-3}$
3.5	$1.264 \pm 1.3 \times 10^{-3}$
4.0	$1.334 \pm 2.3 \times 10^{-3}$
4.5	$1.22 \pm 9.1 \times 10^{-3}$
5.0	$1.111 \pm 3.5 \times 10^{-3}$
"D"	$1.410 \pm 1 \times 10^{-4}$

"D" ≡ swept sawtooth function 2.17-2.53 kHz w/period τ = 11 ms.

From Table II there are two phase modulation programs that yield a nearly equivalent increase in bunch area. The efficiency of beam passage through transition then was involved to distinguish between the two states and define which yielded the "best dilution". Figure 9 gives the envelope of the F-20 wall current monitor for the full acceleration cycle. The amplitude is proportional to the bunch amplitude; all 12 bunches are included. In Figure 9 there are two important characteristics to observe. First, the peak bunch density is greater in the "cavity OFF" case at transition than in the "cavity ON" case. Second, after transition the peak bunch density is greater in the "cavity ON" case than in the "cavity OFF" case.



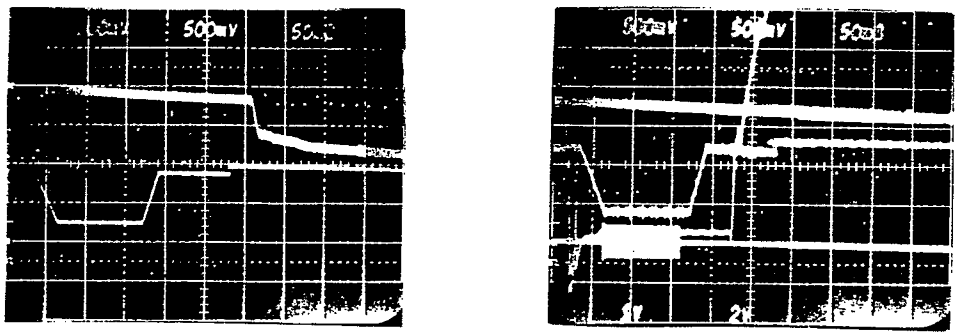
(a) (b)

Figure 9. F-20 wall current monitor envelope for the full acceleration cycle. Peak in both cases is transition. In (a) the VHF cavity is OFF and in (b) the VHF cavity is ON.

The peak on the wall monitor is inversely related to the bunch density, so to restate the last sentence: the peak bunch density before transition is lower with the cavity on than with the cavity off (not surprising -- that is what the cavity is doing), but after transition the peak density is higher with the cavity on than with the cavity off. Part of this effect is simply a ~ 10% beam loss at transition in the cavity off situation which reduces the amplitude in the figure (by about 10%). The bulk of the effect is due to a reduction of transition induced longitudinal blowup which is driven by a high local density. By coming in to transition with a lower than "normal" peak density, we emerge from transition with a higher than "normal" peak density.

Since the beam experiences much less of a perturbation due to reduced space charge defocusing at transition, it retains more of its original character throughout the cycle. With the dilution cavity active, the peak density late in the cycle appears higher than with the cavity off. This could cause instability problems as the AGS intensity increases. However, any conclusion is premature since with the present transition crossing, the unavoidable dilution is not at all smooth, so very high density regions still exist while with the cavity on, the bunches should be smooth though, on average, more dense. This subject needs further study, but experimentally at 1.5×10^{13} no problem was encountered.

While monitoring the AGS analog beam current transformer signal (L-20), the phase modulation program to the VHF cavity was varied. The most efficient passage through transition was achieved with the swept program ("D" of Table II) and the results are displayed in Figure 10 below.



(a) (b)

Figure 10. In picture (a) the VHF cavity is not powered and the L-20 circulating beam current transformer (top trace) shows the ~ 10% beam loss at transition, lower trace is main rf voltage. In picture (b), the VHF cavity is ON and there is almost no perceptable loss of beam on L-20 at transition (top trace). Other traces (top to bottom) are main rf voltage, main magnet voltage, and VHF cavity rf drive. The phase modulation program is swept "D" (see Table I).

The circulating beam current was nominally 1.6×10^{13} protons immediately prior to transition and in the cavity OFF case, the amount of beam lost was $\sim 1.6 \times 10^{12}$ protons (10% loss or 90% efficient). With the cavity powered, however, with the swept program "D" for the phase modulation, the loss was $\sim 2 \times 10^{11}$ protons (1.25% loss or 98.75% efficient). This significant improvement in transition efficiency was consistently reproducible.

As a consequence of this effort and the quite positive results, a decision has been made to include the use of the VHF cavity for normal high intensity AGS accelerator operations this fall. In addition, it is intended to parasitically continue the studies effort to further explore the following:

- power the cavity over a longer period (now 100 ms)
- increase/decrease V_{vhf} (hold f_s = constant)
- detail the swept phase modulation program over 2.0 → 2.25 kHz
- lower further V_{rf}
- determine relationship of f_{vhf}/f_{rf} = (n + 1/3, 2/3, m/12) to the observed "selective bunch" dilution (Figure 4)

References

1. J.M. Kats, IEEE Particle Accelerator Conf. 1281, 1987.
2. AGS Studies Report No. 252.
3. AGS Studies Report No. 251.
4. S. Ohnuma, The Beam and The Bucket - A Handbook for the Analysis of Longitudinal Motion, 22 January, 1986, TM-1381 (p. 4), Fermilab.