

p̄ #446

Bill Kells  
1/20/86

## Instabilities, Chromaticity and $\eta$ in the Debuncher

A large body of observations concerning Debuncher instability exist from the 1985 running. However these were all en passant to the main tasks of commissioning. I have sifted through all documentation again and find that no definite conclusions can be made about the quantitative nature of these instabilities (eg. mode type; number or current threshold for well defined and known lattice conditions; blow up e folding times; interaction with cooling systems). I will summarize this body of observation, and then draw several suggestive conclusions. This will be oriented toward guiding the upcoming (higher intensity!) runs. In particular I will outline procedures to illucidate and diagnose the exact instability situation.

### I Summary

**Overview:** The observed instabilities fall in two general categories. First, "high" current primary proton beam (PPB) induced. Depending on current, bunch number and DRF-1 tune, these caused clear and gross beam  $\epsilon_x$  and  $\delta p/p$  disruption, severely degraded beam lifetime and caused TWT overlode. However the current threshold erratically changed (although no rough correlated documentation of relevant conditions exists) from below 100 $\mu$ A to several ma. Although such instability was not surprising given the  $\eta$  and  $\xi$  of the debuncher and the beam  $\delta p/p$ . The stabilizing time for, e.g., beam lifetime was surprisingly long (up to  $\geq$  1000s !).

Second, benign instabilities persisted with secondary beams ( $\leq$  4-5 $\mu$  Amp). Coherent [Low frequency] lonitudinal motion was observed. The existence of this seemed associated with DRF2 use, and the coherence was apparently "damped" by the transverse cooling. However no blow up of any plane emittance was conclusively observed. The only deleterious effect may have been TWT trips when running with the highest secondary currents ( $\leq$  5 $\mu$ A protons ).

## II High Current Instabilities

During D.B. tuning studies with primary protons we injected beam with the following properties:

Table I

Average Intensity, I (=DCCT) .....	upto -20ma
$\Delta p/p$ (FWHM) .....	0.0015 - 0.004
$\eta$ .....	- 0.0055
$\epsilon_{\perp}$ (inj) .....	2-4 $\pi$ $\mu\text{m}$
$\epsilon_{\perp}$ (coast) .....	8-13 $\pi$ $\mu\text{m}$
$\xi$ .....	-(?)0.1-0.4
#Bunches (@ 53 MHz) .....	up to 20 contiguous
DRF 1 : each of 6-7 cavities:	
Q .....	~ 1.1x10 <sup>4</sup>
R <sub>shunt</sub> /Q .....	~ 180 $\Omega$
Detuning: $v_{res} - v_0$ .....	+~25KHz

Figure 1. characterizes the "settling" down of the multi booster bunch injected beam. The natural debunching time from shearing out of one bunch is - 0.3s(= $\tau_D$ ). Indeed, we always observed "true Schottky" peaks at times  $\geq 100$ s after injection. Such evident self bunching (via cavity impedances: DRF1 in our case) is already well known<sup>[1]</sup>. Special cavities installed in the ISR to investigate such effects showed longtime results strikingly similar to Fig. 1. Since those experiments involved unbunched (initial) beams, we can conclude that our situation, though made perhaps more severe by initial bunching, is essentially due to high current and coupling impedance.

Unfortunately the precise status of DRF-1 was typically unknown. Two situations could be distinguished in the record. First with DRF-1 ~ tuned to  $\omega_0$ . The instability was so severe, Fig. 2, that the initial small  $\Delta p/p$  was smeared over the available ( deceleration direction only) momentum aperture. This was an anomalous situation for coasting primaries, so in the sequel we treat data of the second, "detuned" case, only. By "detuned" we mean that the period of instability after injection did not substantially increase  $\Delta p/p$ , e.g. Fig. 3. The 25 KHz detuned condition of the cavities, table 1, may or may not have been in effect. In section III - IV we show that such a qualitative distinction is plausible.

Fig. 1 is an extreme example. Qualitatively the current ( $I = DCCT$ ) threshold for instability past  $\approx \tau_D$  as observed on Schottkies or lifetime scans, varied from  $-100\mu A$  to over  $1ma$ . It is important to note that this threshold correlated strongly with tuning the injection lines, suggesting a transverse nature of the instability. A more sensitive indicator of instability (or long time residual coherence of the beam) was time plots of low frequency longitudinal band power, and occurrence of TWT tripping. Definite evidence of residual coherence tripping TWT's down to  $I \rightarrow 5\mu A$  exists (Fig. 4 a,b). Although longitudinal coherence persisted down to the lowest currents observable (on Schottkies), NO CONCLUSIVE TUBE TRIPS OCCURED WITH ANY BEAM  $< 5\mu A$ . It was confirmed that the cooling systems themselves did not excite any instability. "old", nomogenized, beam could be cooled (late PIN switched) with no trips (at  $I$  almost  $10x$  what tripped early switched on tubes); and induce no coherence. In some cases (initially heated beam) late switched on cooling could loose some beam, an anticipated stochastic cooling effect.

Further evidence that the instability involves transverse motion comes from Fig 5. The coherent power around  $\sim 2150$  MHz (peaked!) is vested in the lower side band. For the D.B. ( $Q > \text{half integer}$ ). This is the fast wave sideband, which cannot be unstable for any  $\text{Re}(Z_{\text{wall}}) > 0$  for unbunched beams. This indicates that our instability is evidently a complex <sup>interplay</sup> between longitudinal (initial bunching structure) and transverse degrees of freedom. The fact that measured  $\epsilon_1$  was always  $\gg$  carefully injection tuned AP-2 beam  $\epsilon_1$  supports this. Below I show that the  $Z_{\text{wall}}$  stability margin is indeed much less than the longitudinal margin.

### III $Z_{\text{wall}}$ for D.B.

The following are calculated using known D.B. properties:

$$\frac{Z_{11}}{n} = [15.4i + (1-i) 1.06] \text{ Ohms}$$

↖ n=9

which is a blend of naive pipe  $Z$  formula and bellows, valve, box, etc. contributions from B. Ng's  $\bar{p}$  Note # 314. Beam  $1/2$  height =  $8mm$ .

$$\left| \frac{Z_{11}}{n} \right|_{\text{Keil, Schnell}} < 5.1 \times 10^5 \Omega \text{ ma} \quad (\Delta p/p = 0.002)$$

$$Z_{\perp} = [18.0 \times 10^6 + (1-i) 3.6 \times 10^5] \Omega/m$$

↖ n=9

$$|Z_{\perp}|_{K, Sch.} < 7.3 \times 10^8 \Omega \cdot \text{ma/m} \quad (\Delta p/p = 0.002)$$

This is for a worst case; for  $n=Q$  and where  $\xi = 0.1$  dominates the frequency spread.

Notice that this sets a naive current threshold of 86 ma.

DRF 1 impedance is not included in the above:

$$\begin{aligned} Z_{\text{Drf1}} &= 1.2 \times 10^7 \Omega \quad \frac{1 - 2i \Delta}{1 + 4 \Delta^2} \quad (\text{near resonance}) \\ & \quad \Delta = Q (\omega_{\text{res}} - \omega) / \omega_{\text{res}} \\ &= 1.2 \times 10^7 \Omega \quad \text{on resonance} \\ &= -1.1 \times 10^4 \Omega \quad \text{detuned by 25 KHz} \end{aligned}$$

This seems uncomfortably high but is essentially purely reactive (inductive). Fortunately we are above transition so this is the correct sign for negative mass stability; i.e. we want to detune DRF1 as it has been. Similarly the Robinson instability cannot occur for this  $\eta$  and this detuning direction.

#### IV. Chromaticity ( $\xi$ ) and $\eta$ in D.B.

For a complete discussion of [especially bunched beam] instabilities we must know  $\xi$  and  $\eta$  precisely. Unfortunately  $\xi$  was "set" once to "zero" and not further studied. From turn by turn Fourier transform tune peak widths  $\Delta Q$ 's (FWHM) as low as 0.002 (see Fig 6) were documented. On other occasions of normal D.B. running this value was as high as 0.007. Notice that even this minimum  $\Delta Q$  gives  $|\xi| \geq 0.1$ .

This method does not give the sign of  $\xi$ , important for transverse stability. Several existent, quiescent beam, Schottky scan pictures (~2GHz) suggest that lower sidebands were slightly wider than uppers. This says  $\xi/\eta > 0$ . Quantitatively these records give  $|\xi| \sim 0.16$ ; in good agreement!

If such signs and values are correct the " $\xi$  spread" and " $\eta$  spread" tend to cancel (at least for the slow wave sideband). A certain mode number  $n$  will have minimum net sideband spread and hence be most critical for stability. Since  $\eta$  is so small this will be a high  $n$ , just where we expect large  $Z_{\perp}$  enhancements from discontinuities<sup>[2]</sup>.

$$n_{\text{critical}} \approx Q (1 + \xi/\eta) \approx 550$$

It is just possible that we might have missed such a cross-over since the UHF bands were never explicitly studied. the unstable "peak" in Fig. 5 could indicate such behavior, through some what high in  $n_c$ .

In any case this suggests a good way to measure  $\eta$ . Sextapoles could be detuned to give a "large" negative  $\xi$  (i.e. one easily measured with precision on T-T display). If this detuning moves  $n_c$  into the cooling band we can measure  $n_c$  and hence  $\eta$ . Note that we would like to ensure  $\xi$  positive from the stability point of view (This turns out true also in the case of relevant bunched beam instabilities<sup>[3]</sup>).

## V. LOW CURRENT INSTABILITIES

For all cases of D.B. injection with beams  $\leq 5\mu\text{A}$  no deleterious instabilities were found. For instance even with primary protons it was possible to run the TWT's at nominal power, CW (no PIN switching). However a longitudinal coherent signal persisted for 10's of seconds (Fig. 4a). No significant transverse coherence was observed (Fig. 4b).

More puzzling was that the transverse cooling effectively damped the coherence on a time scale  $< 10\text{msec}$  (Fig. 4b). Some evidence indicated that DRF2 being on also was necessary for this coherence. Fig. 7 shows the large pick up of DRF2 imposed structure. We should easily be able to determine whether the coherence is merely this DRF2 structure. The puzzle remains of how a transverse system damps it (at how many harmonic components?). Note that we also have evidence of such coherence for  $< 5\mu\text{A}$  primary proton injection when DRF2 was off. This complication could be avoided (or perhaps clarified) by changing the longitudinal Schottky monitor harmonic from  $h=127$  to, say,  $h=4 \times 33=132$  since the Fourier spectrum of the barrier bucket has nulls at multiples of 4.

## VI Coherence from DRF1

Let's estimate the effects of [detuned] DRF1 on bunched beams (primaries). Especially at high injected currents, we observed dragging of the beam distribution in energy to lower energy (Fig. 2, but also similar behavior in the Accumulator and elsewhere<sup>[1]</sup>). Note from Fig. 2 that if DRF1 were detuned fully we might expect dragging by  $\sim +25\text{KHz} \times 75/53 = +35\text{KHz}$ , whereas only about half this is ever observed. Furthermore the beam then stabilizes (debunches fully) dissipating no further power to the cavity (since we are negative mass stable).

Using the impedance of section III, one calculates a " $V_{RF}$ " = 113 volts for an initial fully bunched (53MHz), 5ma, injected beam driving DRF<sup>1</sup>, Fully detuned. At  $h=84$  and the low D.B.  $|\eta|$  this implies a bucket height of  $\sim 0.7$  Mev or  $\sim 20\%$  of the injected beam width?! Similarly, the real part of  $Z_{cav}$  can be used to calculate the energy dissipation. This gives a rate for a "captured" portion of the beam smearing toward cavity resonance of  $+10\text{KHz}/5\text{sec}$ , in reasonable agreement with observed.

Extrapolating this reasoning to low intensity ( $\sim 1\mu\text{A}$ ) shows that the smearing rate is too slow to be discerned. However the coherent perturbation can easily exceed the Schottky signal, at least at the cavity harmonic.

### VII Measuring $Z_{wall}$

In particular I have some suggestions for  $Z_{\perp}$  measurement techniques. The concept is old<sup>[4]</sup>; that coherently kicking a coasting beam at a will give full information on  $Z_{\perp}(\omega)$  if we observe the oscillations at a suitable pickup. Since the kicked beam elicits a wall response we see it as part of the total response to the kick. The problem technically is to accurately separate out the  $Z_{\perp}(\omega)$  from total response.

consider the transverse case:

$$\text{response, } \chi_{\perp}(\omega_D) = \frac{G_D e^{i\phi} + G_W(\omega_D)}{(\omega Q)^2 - (n\omega - \omega_D)^2}$$

where  $\omega_0$  = revolution frequency

$\omega_D$  = Driving frequency (kicker)

$\phi$  = Azimuthal phase : kicker - pickup

$G_D$  is the kick amplitude and  $G_W$  is the net ( $2\pi$  azimuth integrated) wall force =  $i K Z_{\perp} \langle \chi \rangle$  with  $K$  a positive constant. Assume (good approx. for D.B.) that the resonant denominator can be expressed into two entirely separate parts, i.e.

$$\begin{aligned} [(\omega Q)^2 - (n\omega - \omega_D)^2]^{-1} &\approx \{2Q_0\omega_0[\omega_D - (n - Q)\omega]\}^{-1} \\ &\quad - \{2Q_0\omega_0[\omega_D - (n + Q)\omega]\}^{-1} \end{aligned}$$

so that there is an entirely separate contribution from each sideband. For each sideband we solve, in the usual self consistent way, for  $\langle \chi \rangle$ :

$$\langle \chi \rangle_{\pm} = \mp [G_D e^{i\phi} + iK Z_{\pm}(\omega_D) \langle \chi \rangle_{\pm}] \frac{1}{2Q_0 \omega_0} \int \frac{f(\omega) d\omega}{\omega_D - (n \pm Q)\omega}$$

Then

$$(\langle \chi \rangle_{\pm})^{-1} = \pm J_{\pm} - iK Z_{\pm}(\omega_D)$$

so that naively we can get  $Z_{\pm}(\omega_D)$  by subtracting the response of adjacent sidebands:

$$-iK Z_{\pm}(\omega_D) = 1/2 (\langle \chi \rangle_{+}^{-1} + \langle \chi \rangle_{-}^{-1})$$

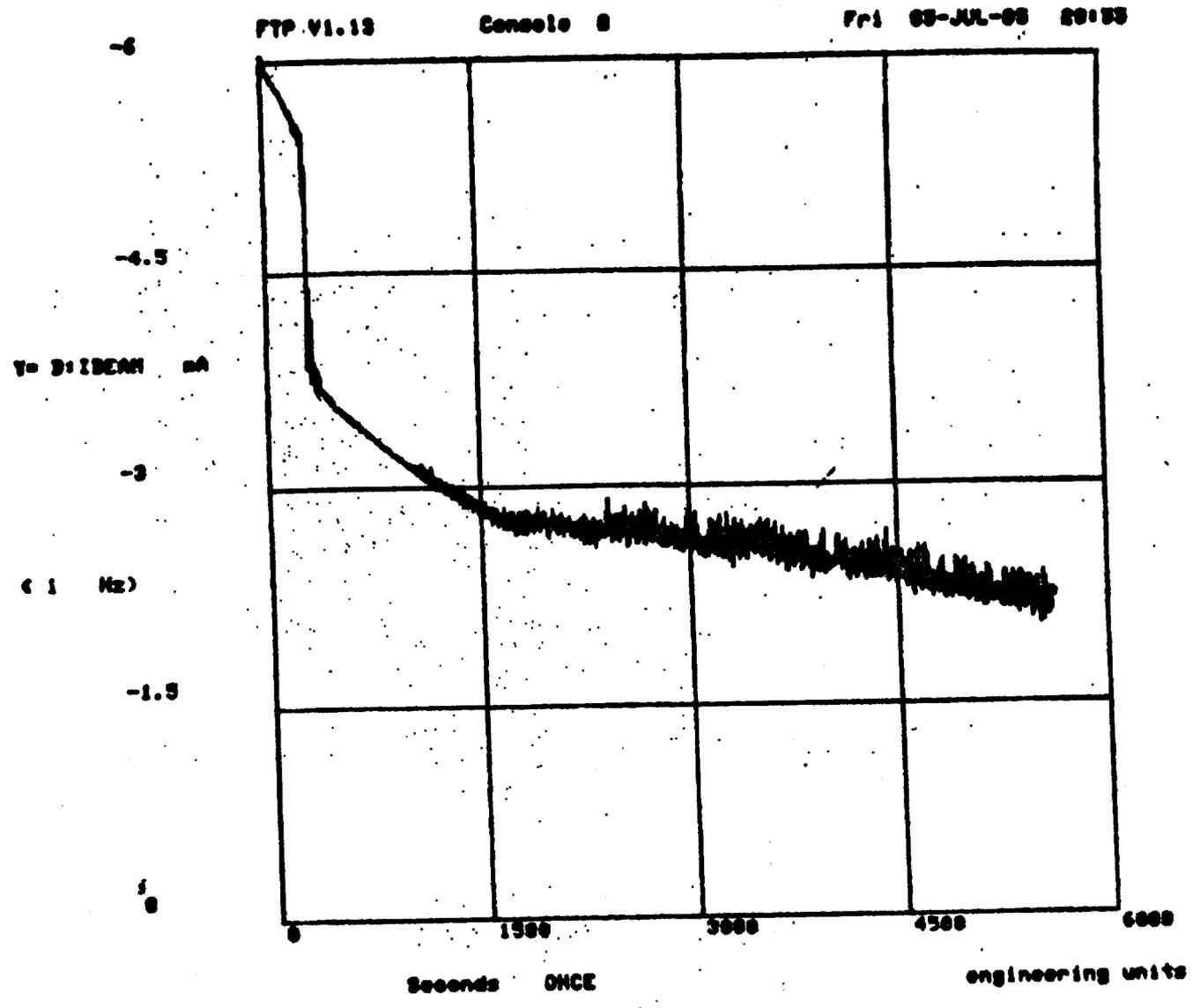
This would be an easy exercise in network analyser data manipulation. Note that we depend on  $J_{+}$  and  $J_{-}$  being equal in magnitude, which certainly is not the general case for  $\xi \neq 0$ . In any case we can study rapid, resonant, changes in  $Z_{\pm}(\omega)$  by comparing the same sign sidebands: one on and one just off resonance.

REFERENCE

1. "experimental Investigation of the coherent Longitudinal instability of Relativistic Particle Beams", B. Zotter, & P. Bramham, Proc. Intl Conf. on Accelerators, 1976.
2. See F. Sacherer in CERN PUB. 77-13 (1977)
3. "Head-Tail type instabilities in the CERN PS and Booster", J. Gareyte and F. Sacherer, Proc. Intl. Conf. on Accelerators, 1978.
4. "Information from beam response to longitudinal and transverse Exatation", J. Borer, et.al. IEEE trans N.S. -26, 3405 (1979)

Friday, July 5

FIGURE 1



beam after capture, no change, made in Debuncher after beginning of start. No explanation for fast beam loss at about 1000 sec.

Aug 29th

FIGURE 2

2025 MR beam reported as imminent by MER

2109 Tuning up A1-1 on intermittent beam

2143 DB injection tuned up, Check operation of  $\Sigma 13$ : works OK (updates in 5s)  
However orbit looks very scary.

2205 Extract to the Accumulator ~~with~~ with Qop in beam at the end of 20 cycle.

Acc. Injection efficiency is poor: most of the beam seems to be lost in on the 1st turn  
 Start looking at loss monitors: see large losses on LMAAM

2220 Main Ring ramp trip.

100 Aug 30

Beam was injected into the Debuncher. It was noted that the beam spread in

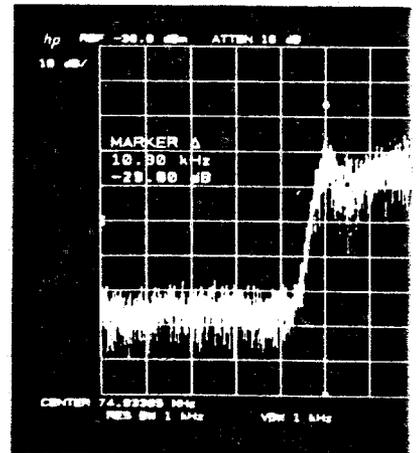
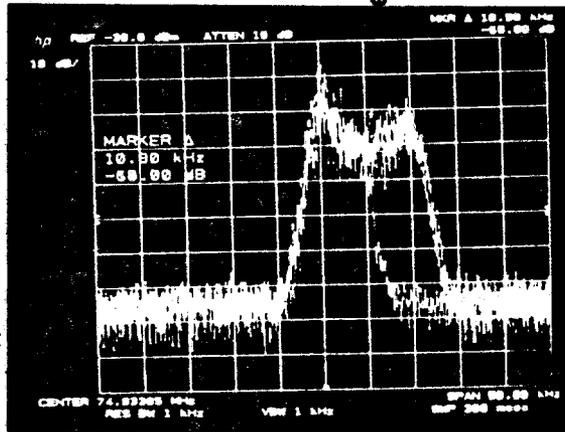
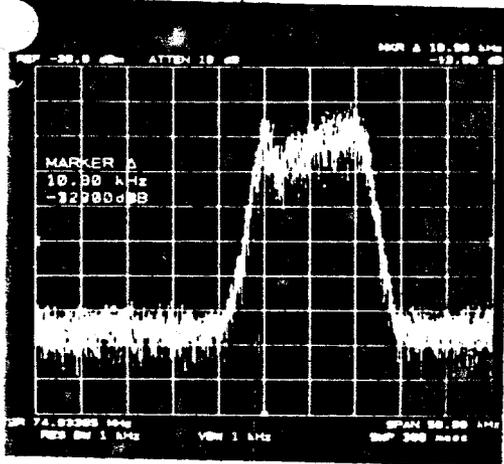
A debuncher blew up to 2% almost immediately. The following pictures were

taken before the Main Ring went down.

→ Mass filter was turned  
 what was ~~DRF~~ turned  
 Heaters are  $\approx 100W \Rightarrow f =$   
 momentum

that the beam spread in

note previous trace with narrow width



12.5 ma and a full batch 1.2 ma and a partial batch 0.25 ma and a part

in each case the ~~beam~~ current/bunch is the same. One notes that the

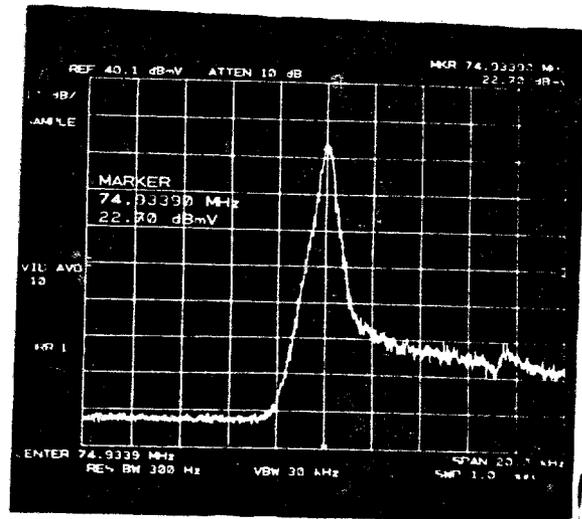
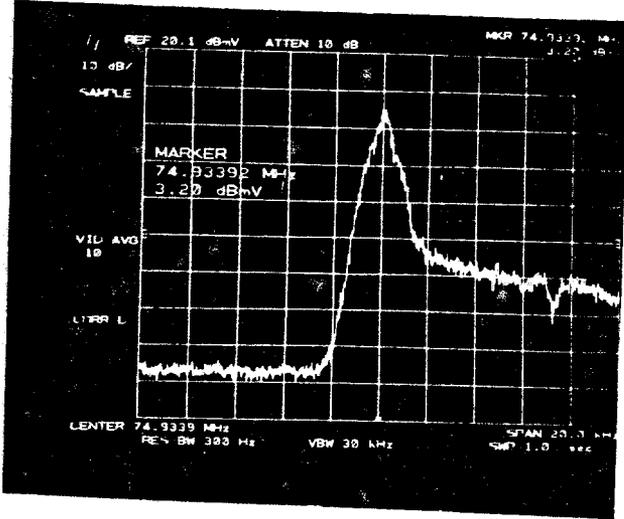
frequency spread is the same in all cases after 300-600 nsec.

Center frequency = 74.93385 MHz ; SPAN = 50 KHz Spectrum Anal Settings

$$\Delta f = 12 \text{ kHz} \quad \frac{\Delta f}{f} = \frac{12 \text{ kHz}}{74,950 \text{ kHz}} = 1.6 \times 10^{-4} \quad \left| \frac{\Delta P}{P} = |\eta^{-1}| \frac{\Delta f}{f} = .027 \right.$$

The momentum spread is:  $\eta = .005 \quad \Delta P \approx 3\%$

any residual Schottky signal in the Debrancher - when beam is stored for long periods  $T \gg 4$  sec.



Debrancher current = 4 ma

Debrancher current = 12.5 ma

cavities detuned  $\sim 30$  kHz

The problem of page 259 is gone. When the above traces are measured on a linear scale the full width at half maximum is  $\pm 1.5$  500f corresponding to a momentum spread of 0.133% FWHM.

3:18 John Morrison continues on the store of three hours ago.

The Debrancher injection has been tuned up to reduce the coherent oscillation.

MULTIPLE TURN DISPLAY, SECTOR D6 MUX

Date, Time: 08/31/85 0319

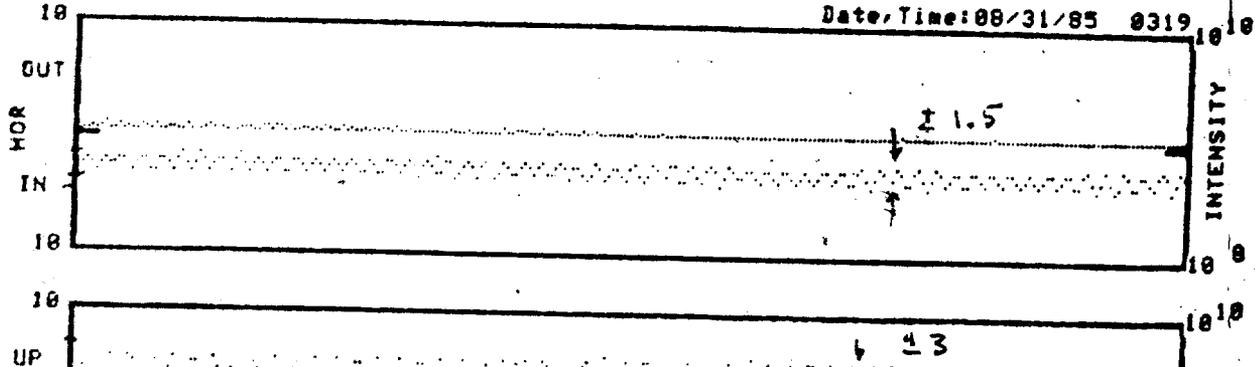
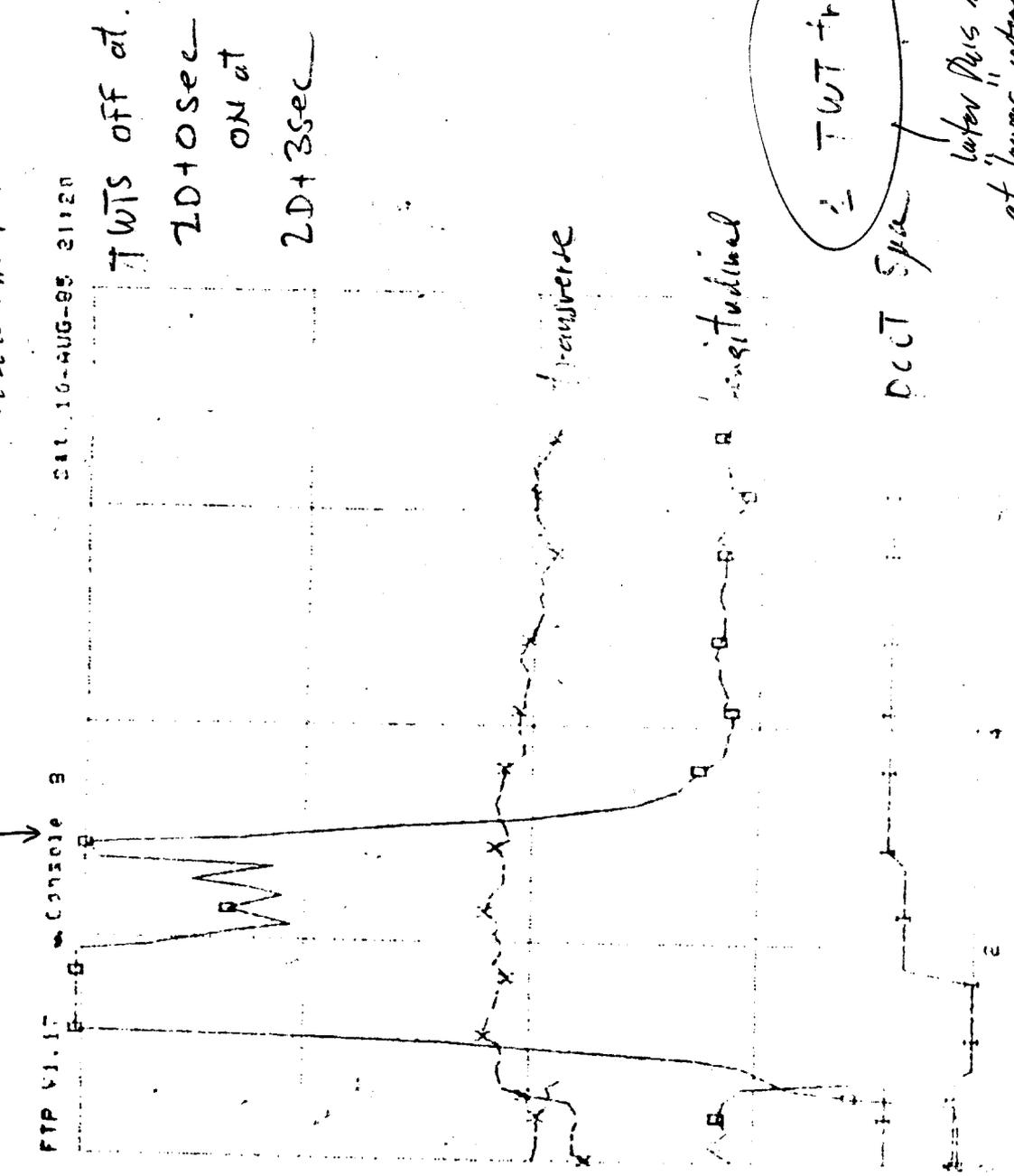


FIGURE 4A

many pics in this group  
- all consistent

cooling on.



EVENT 20 -1

1.05

0.75  
0.75  
-0.0375

REFLECTIVE VOLT 0  
DISPECY VOLT X  
PIBEAM MA 1

0.5  
0.025  
0.15 HZ  
0.15 HZ  
0.15 HZ

0.03  
0.0125

later this night  
at lower intensity  
≈ 5 μa -  
noted that no frips  
occured.

Turning off

- M: Q108
- M: Q109
- D: Q701
- D: Q702

Cham was just DB was  
freshly inj. tuned (csh. osc.)  
just prior to these pages.

and { reducing D: Q707 from 111 to 70 a.  
reducing collimators 707, 708 from 60 to

Turned off DRF3 (D: R3LLAM)

comment made by V. ...

Note to Jeff Sanner: Your comment regarding not turning off KIM bin power to turn off Debuncher RF systems (see Page 82) indicate how not to do it but does not indicate the proper method. Please indicate the proper procedure below to turn OFF Debuncher RF systems. (1 line maximum each)

System

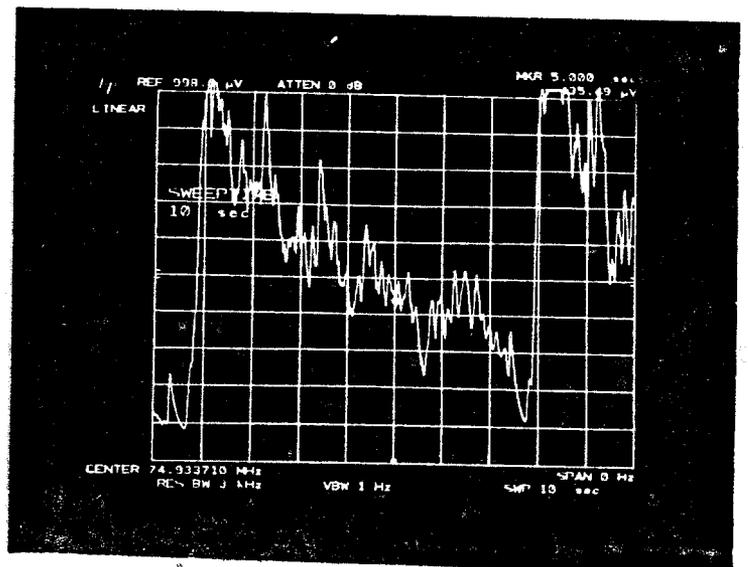
Procedure

- DRF1
- DRF2
- DRF3

On 7 sec Debuncher cycle, large amplitude fluctuations observed in the power in the 127<sup>th</sup> harmonic of the revolution frequency Schottky signal implying possible interaction of beam with environment, even at 20 pA circulating. This instability may be related to the tripping of stochastic cooling equipment (not out for these measurements)

Spectrum analyzer time plot of power (amplitude actually) in 127<sup>th</sup> harmonic of rev frequency vs time (linear scale)

DCCT does not show this structure. It does not seem to be in transverse Schottky signal either. See hardcopy log for plot of DCCT, longitudinal schottky, and transverse schottky.



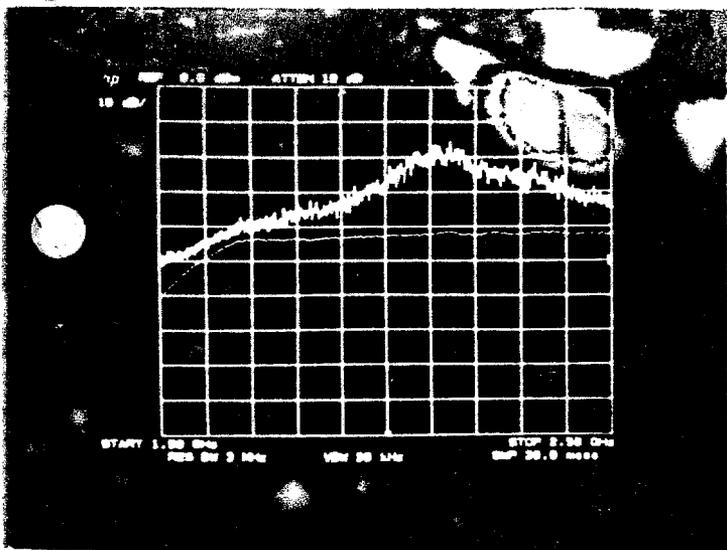
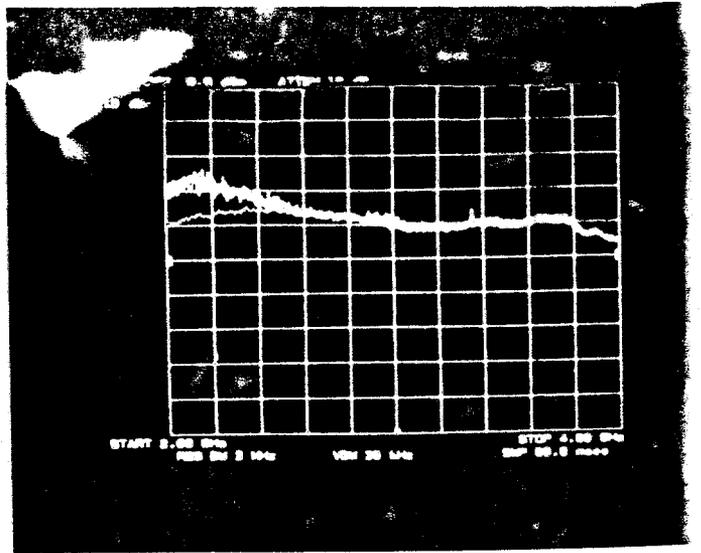


FIG 5



BRIGHT = MAX HOLD

~ 80  $\mu$ A

BRIGHT: 711 H PU'S @ SCH PORT ~ 80  $\mu$ A  
 LITE: NO BEAM (MAX HOLD)

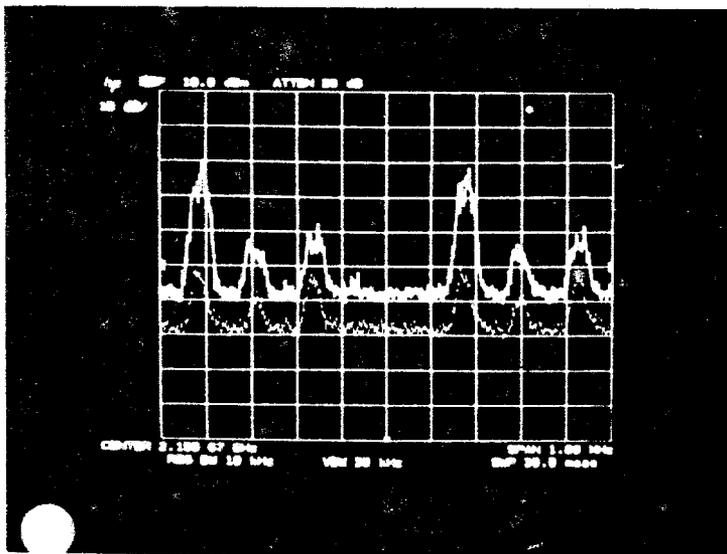
MAX HOLD ~ 80  $\mu$ A

LITE: LATE TRUE SCHOTTKY SIG  
 BRIGHT = MAXHOLD WITH BEAM  
 80  $\mu$ A After beam sett. (i.e. DC)

WHERE IS THE DB "INSTABILITY" (WHICH TRIPS TWTS OFF?):

REQUIRE: A FAST TRANSIENT POWER CONCENTRATION AROUND 2150MHZ IS OBS AFTER INJECTION ON TRANSVERSE STOCHASTIC PU'S

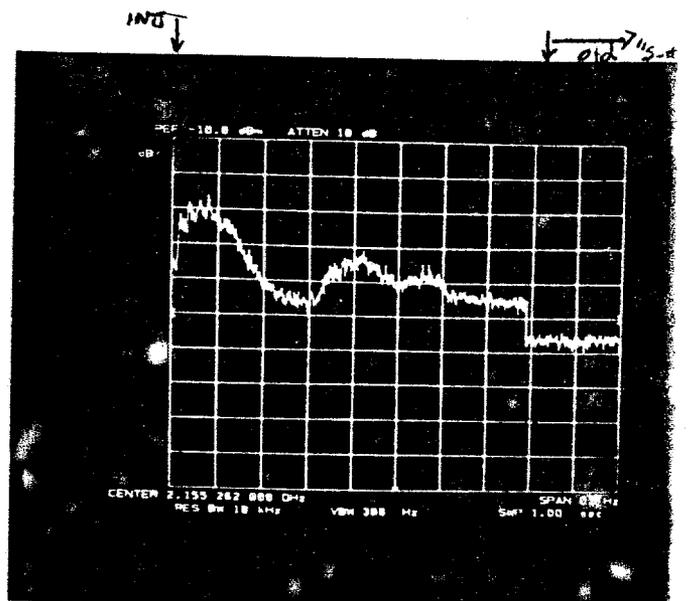
2-3-81 MAX HOLD TECHNIQUE LOOK AT INDIVIDUAL BANDS @ PEAK OF INSTA  
 BRIGHT TRACE INCLUDES INJECTION TIME; LITE TRACE = LATE "TRUE SCHOTTKY SIG"



TRUE SCHOTTKY ~ 90  $\mu$ A (DECT)

MAX HOLD

(ARTIFICIAL BASELINE OFFSET)

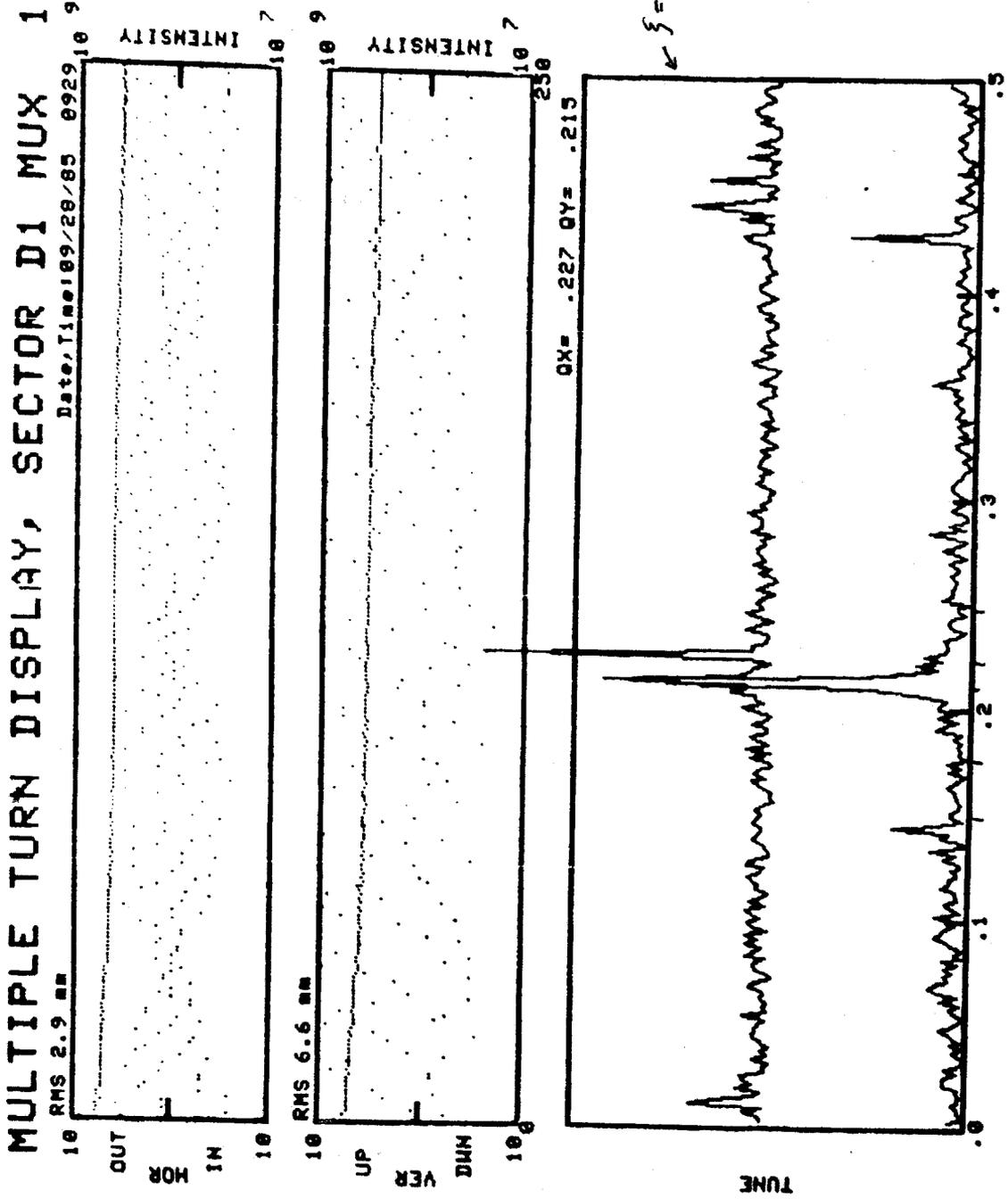


NOT MAX HOLD

DOCT ~ 11

FINALLY, TO SEE EXACT TIME STRUCTURE "ZERO SPAN" ONE OF THE LOWER SIDEBANDS IN (if Rev. H. is "SPANED" THIS TRANSIENT NOT S

FIG 6

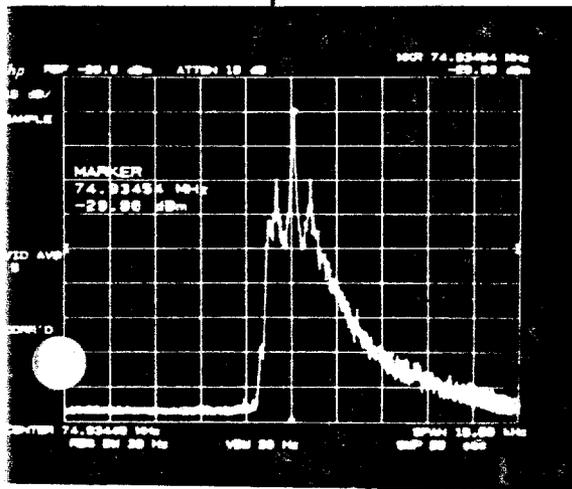


(2) THE LONGITUDINAL BY-TURN DISPLAY (DEBUNCHER) FOR  
50, 45, 40, 35 KV. (SEE HARD COPY LOG).

DEBUNCHER ACCEPTANCE WITH SEPTUPOLES  
(AND DIA LINE QUADS. DETUNED).

SEE HARD COPY LOG; DATA TOO HARD TO INTERPRET.

43100



DRF2 ON

①

NOTICED EFFECT OF DEBUNCHER BEAM GAP ON DEB. LONGITUDINAL PICK THIS IS A LARGE EFFECT AND MAY POTENTIALLY CONFUSE BEAM INTENSITY MEASUREMENTS USING THE DEB. LONG. SCHOTTKY, AND REVOLUTION FREQ. MEAS.

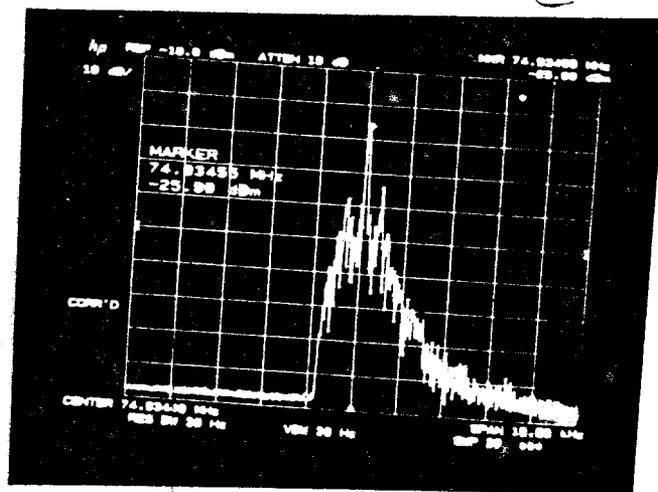
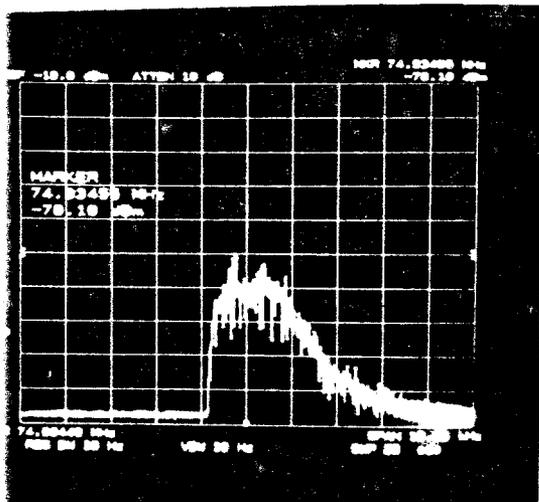
IT SHOULD BE NOTED THAT ONE:

② OBSERVES SYNCHROTRON SATELLITES (DF = 350 HZ)

③ FIGURES 2, 3 ARE FROM THE SAME DATA POINTS.

DRF2 ON

③



in the DB. Heated with steel cooling fingers: small effect. see H. Copies (see note on page 173)