SL-MD Note 87

Accumulation of Bunch Trains

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Summary

This was the first MD on bunch trains. Four e^+ trains with three bunches each were assembled in LEP in bunch current steps of 0.1 mA. A maximum current of 3.6 mA was reached. At 0.3 mA bunch current, the first bunch in each train is stable. The second and third bunches are vertically blown up on the streak camera. Their horizontal and vertical positions on the WB system in LSS7 oscillate. On the Q-meter display, the horizontal $m = -1$ mode is about as strong as the Q_x signal; the vertical spectrum is clean. The BOM system works at a bunch spacing of 32 RF wavelengths. Much data were taken for higher-order mode losses.

1 Aims of the Experiment

The aim of the experiment was accumulating four bunch trains with up to three bunches each, observing how well the mechanics of assembling bunch trains works, and studying the wakefield effects with the observational tools available, i.e. a sum pickup in the RF system, a wide-band position monitor in LSS7, and the streak camera in the optical laboratory. The bunch spacing was 32 RF wavelengths because the BOM system does not allow a readout of the position of the first bunch with a smaller spacing [1]. The bunch current was supposed to be kept below 0.45 mA in order to be sure that the higher-mode losses remain below 200 W per s.c. cavity.

2 Assembly of bunch trains

Assembling bunch trains [2] was surprisingly simple and efficient. We typically filled 0.1 mA into the first bunch of all four trains, using the bunch equalizer to stop injection. We then increased the bucket number by 32 units, increased the bunch equalizer setting by 0.1 mA, and filled into the second bunch. Here we profited from the fact that the beam current transformer cannot distinguish between bunches in a train. Then we increased the bucket number by another 32 units, increased the bunch equalizer setting by another 0.1 mA, and filled the third bunch. We then repeated the whole process to achieve 0.2 and 0.3 mA in a bunch. At that point we reached a software limit in the bunch equalizer which does not allow entering a current beyond 1 mA. Injection and assembly went so well that we omitted to measure the losses on the circulating bunches caused by the injection into other bunches in the same bunch train.

3 Collective Phenomena

3.1 Observations with the streak camera

Figures 1, 2 and 3 show top and side views of the first, second, and third bunch in the train at 20 GeV with 0.3 mA per bunch. The first bunch is stable, the second and third bunch show progressively more vertical blow-up. Figure 4 shows vertical head-tail oscillations of the third bunch at 20 GeV, before the reduction of Q'_x and Q'_y mentioned below.

3.2 Observations with the Q-meter

The horizontal $m = -1$ mode is very visible in the tune spectrum at 20 GeV for a beam current $I \approx 3.2$ mA. The vertical spectrum is clean. These data were taken after changing Q_s from 0.079 to 0.075, and after reducing both Q'_x and Q'_y by one unit which reduced the amplitude of the horizontal $m = -1$ mode signal. Both tune spectra at 45 GeV for a beam current $I \approx 3.4$ mA are clean. Since the Q-meter measures only the first bunch in a train [1], there is no contradiction between Q-meter and streak camera.

3.3 Observations with the wide-band BPM in LSS7

A wide-band BPM in LSS7 was connected to a digital oscilloscope in UJ76. The intensities and the horizontal and vertical positions were displayed on three traces, and sent to the PCR on a TV channel. Figure 5 shows a recording of a bunch train with 3 bunches of about 0.3 mA each at 20 GeV. Figure 6 shows a recording of the same bunch train later at 45 GeV. While the current in the first bunch remained the same, the currents in the second and third bunch dropped. The average lifetimes for all bunches were about 40 hours at 0.1 mA and 0.2 mA, and about 4 hours at 0.3 mA. The lifetimes for the second and third bunch were estimated from Figures 5 and 6. They were 8 hours and 2 hours, respectively, at 0.3 mA.

3.4 Observations with monitors in the RF system

The most striking observations with monitors in the RF system concern longitudinal oscillations of the bunches in a train. Figure 7 shows the Lissajou figures for bunches no. 1 and 2, and for bunches no. 1 and 3, and demonstrates that bunches no. 1 and 2 oscillate at the same frequency, and at a constant phase, while bunches no. 1 and 3 oscillate at different frequencies. The reasons for this behaviour are not understood. We saw bursts of longitudinal oscillations on the third bunch. The differences of the stable phase angles between the first and the other bunches were measured twice. At 45.6 GeV, they were −3.3° for the second bunch, and −5.3° for the third bunch, at a beam current of 3.2 mA. At 44.125 GeV, the angles were $-3.3°$ for the second bunch, and $-6.0°$ for the third bunch, at a beam current of 3.0 mA. The error on the phase reading is about $\pm 0.5°$. The synchrotron tune Q_s was about 0.0697 for all three bunches in a train. One can calculate that the circumferential voltage needed to achieve this value of Q_s is about 270 MV, while the logging of the RF system yields 263 MV, in good agreement. Assuming that the stable phase angles for the bunches adjusts themselves such that the synchrotron radiation losses are compensated, one can calculate voltages of 270, 244 and 226 MV for the first, second and third bunch. These voltages can in turn be used to calculate Q_s for the three bunches. One finds $Q_s = 0.0697$, 0.0651 and 0.0618, in complete contradiction to the observations.

4 Higher-Order Mode Losses

The detailed results of higher-mode loss measurements on the s.c. RF cavities are given in the Appendix. Data were taken for 4 equidistant bunches at 0.5 mA each, and for 4 equidistant bunch trains with 3 bunches each at 0.1, 0.2 and 0.3 mA each. With bunch trains, the variation of the losses between cavities is much larger than with individual bunches. This is believed to be due to the response of RF cavities to bunch trains [3]. The highest loss, in cavity no. 3, is almost as high as the loss calculated by adding all higher-order mode fields in phase at $k_{||} = 0.22$ V/pC. Cavity no. 3 has a resonance at 639.3 MHz which is a bad value for a bunch spacing of 32 RF wavelengths [3].

5 Technical observations

- On the first attempt of injecting into the second bunch, we accumulated 34 RF wavelengths behind the first bunch, although we had dialled in 32. We understand that before our MD the bunches were injected 2 buckets away from the correct buckets. This raises doubts about the resetting of the bunch address counter.
- The BOM system is supposed to read the position of the first bunch in a train, provided the bunch spacing is at least 30 RF wavelengths, recorded as orbit.p_15-30-16. We measured the difference between orbits with one and more bunches in a train and found that it was small. We noticed that the differences were higher for the WB than for the NB monitors.
- The software of the bunch equalizer does not expect bunch train currents beyond 1 mA, and prevents such currents from being accumulated. This should be changed.
- Software automatically changes the gain of the WB system with the bunch current when the standard defaults are used. For bunch trains, the defaults should be changed which is easily done from PCR.
- The narrow band system does not work with five bunches in a train.

- The beam current transformer does not see the fifth bunch in a train. According to Bovet, this can be overcome by storing the bunches in a train symmetrically around the conventional bunch addresses, i.e. at -64, -32, 0, 32 and 64 units.
- The software which computes the incoherent tunes from the coherent ones assumes single bunches with the standard defaults. For bunch trains, the defaults should be changed which is easily done from PCR.

References

[1] C. Bovet, ed., SL/Note 93-54 (BI).

[2] E. Keil, CERN SL/93-27 (1993).

[3] Minutes of the tenth meeting of the bunch train study group, 22 June 1993.

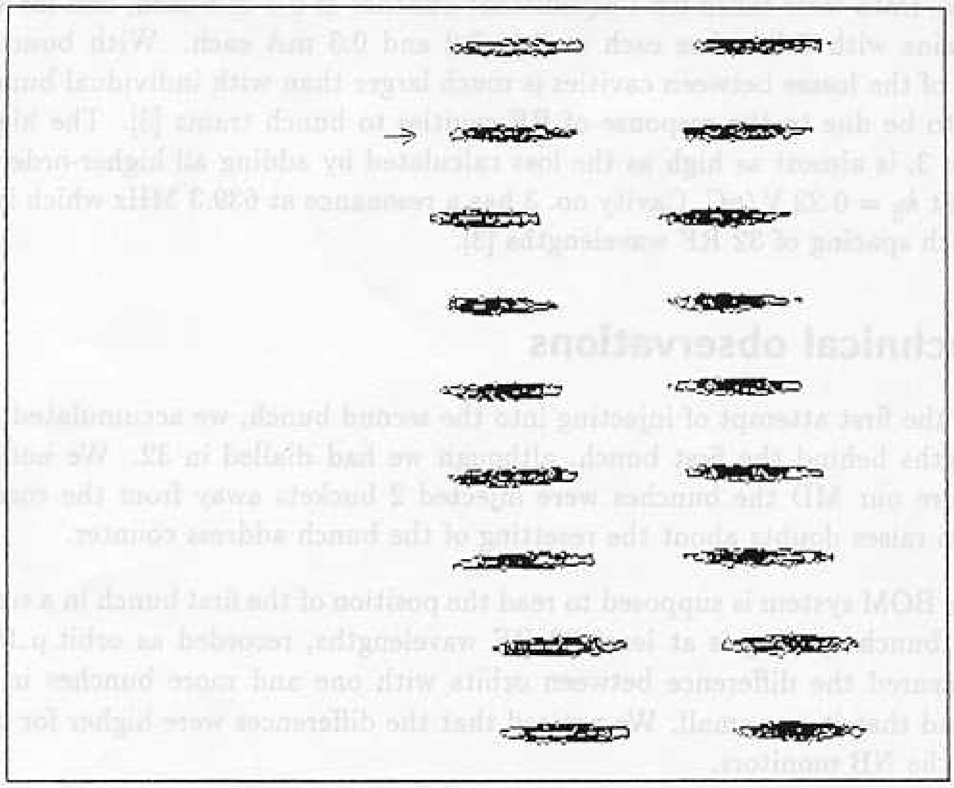

Figure 1: Top and side view of the first bunch in a train at 20 GeV with 0.3 mA per bunch. The top view is at the left.

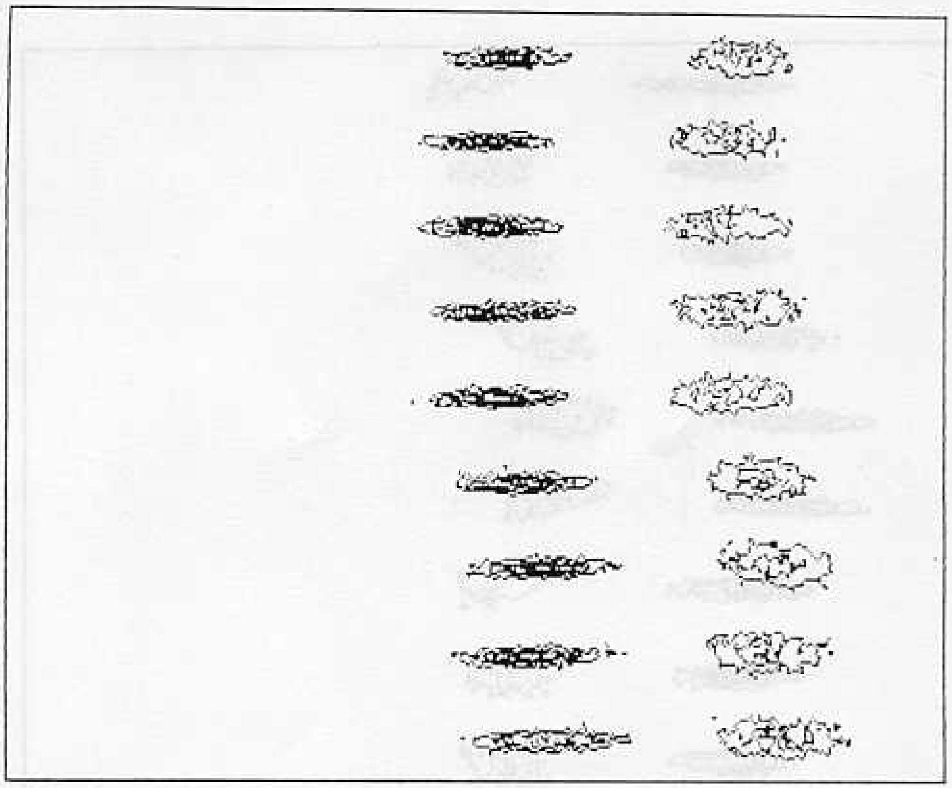

Figure 2: Top and side view of the second bunch in a train at 20 GeV with 0.3 mA per bunch. The top view is at the left.

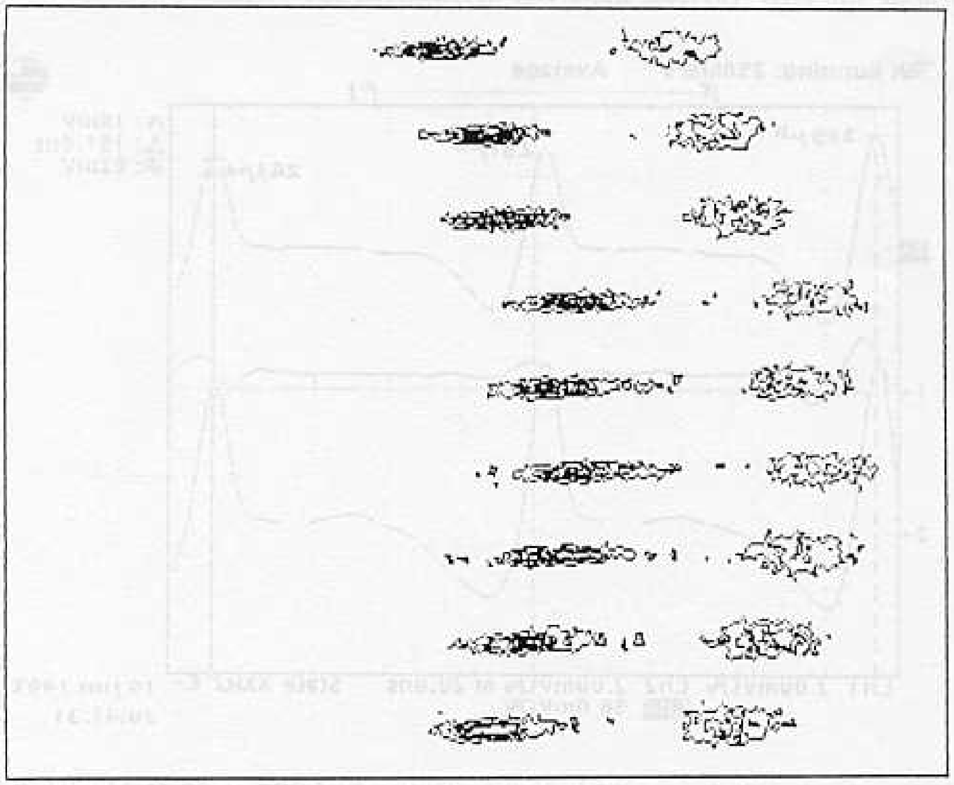

Figure 3: Top and side view of the third bunch in a train at 20 GeV with 0.3 mA per bunch. The top view is at the left.

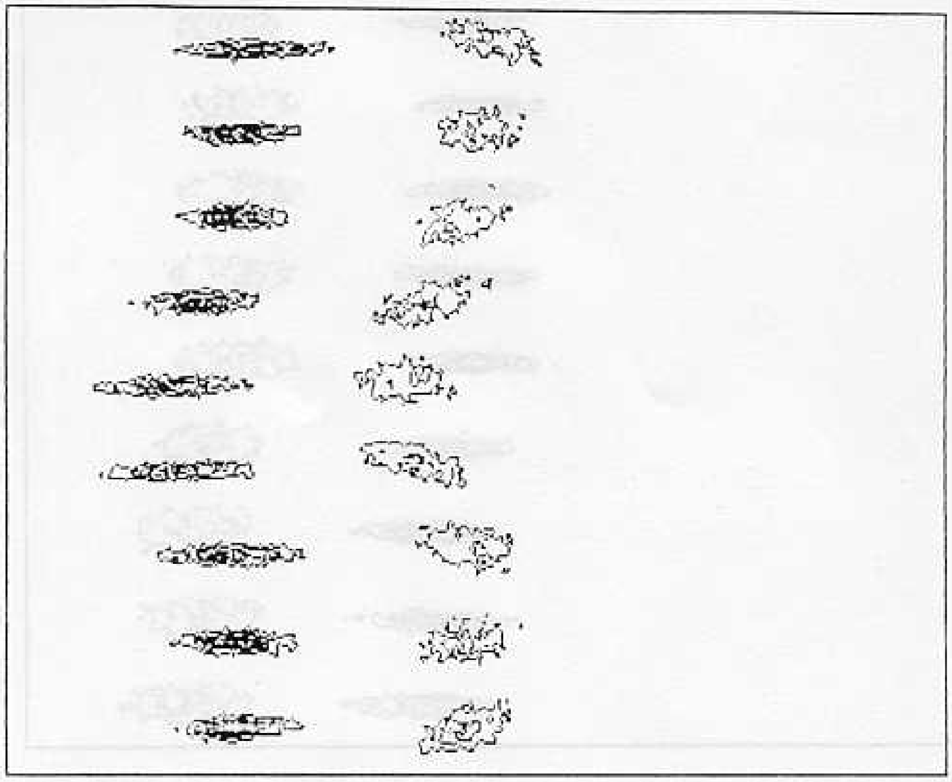

Figure 4: Top and side view of the third bunch in a train at 20 GeV with 0.3 mA per bunch. The top view is at the left. Vertical head-tail oscillations are visible.

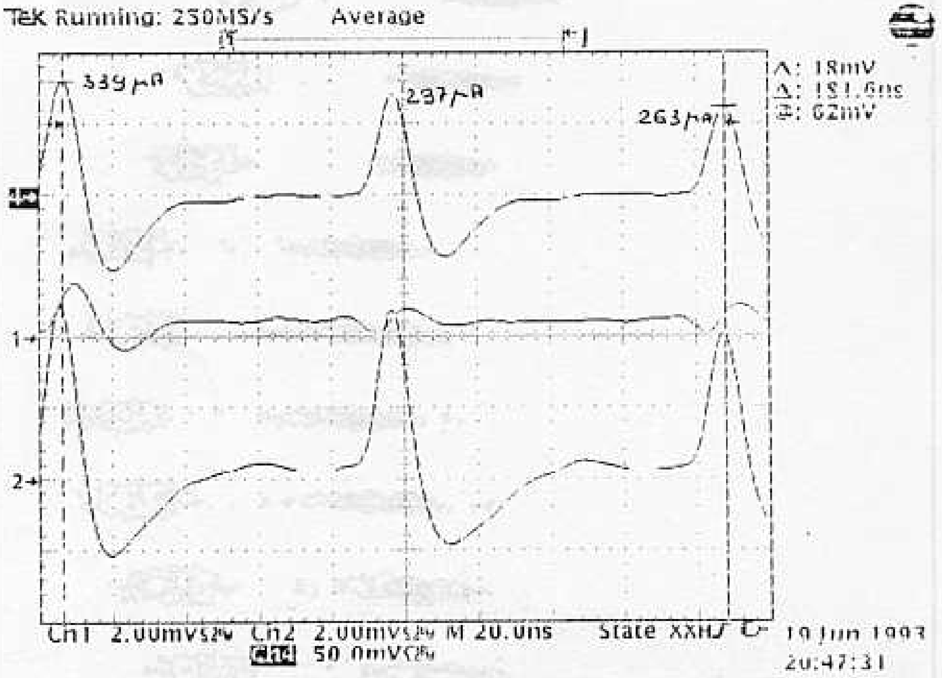

Figure 5: Bunch train signals from a wide-band monitor in LSS7 at 20 GeV with 0.3 mA per bunch. Top trace intensity, middle trace horizontal position, bottom trace vertical position.

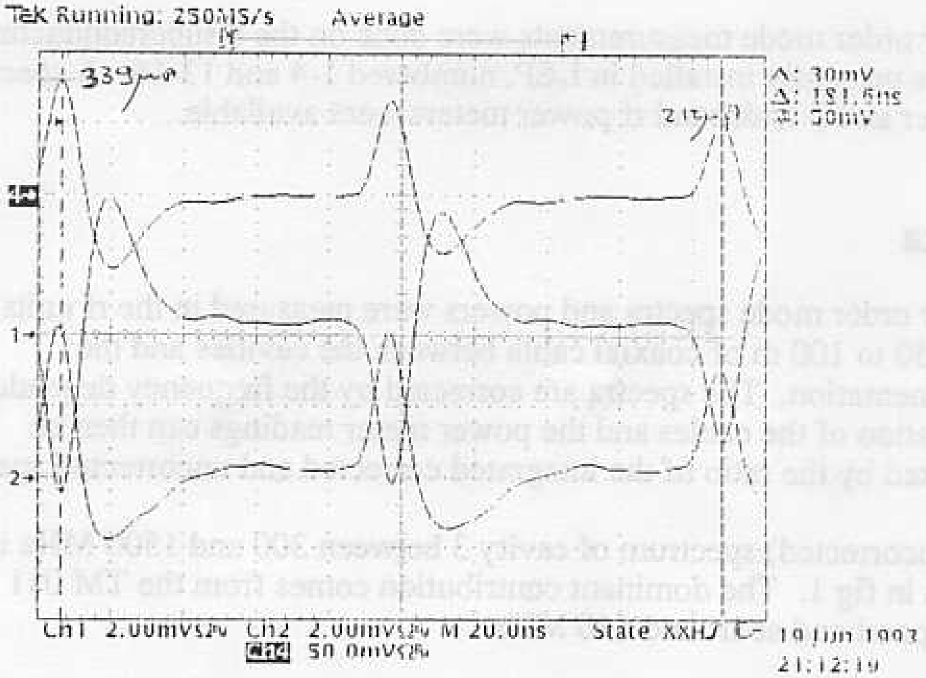

Figure 6: Bunch train signals from a wide-band monitor in LSS7 at 45 GeV with 0.3 mA per bunch. Top trace intensity, middle trace horizontal position, bottom trace vertical position.

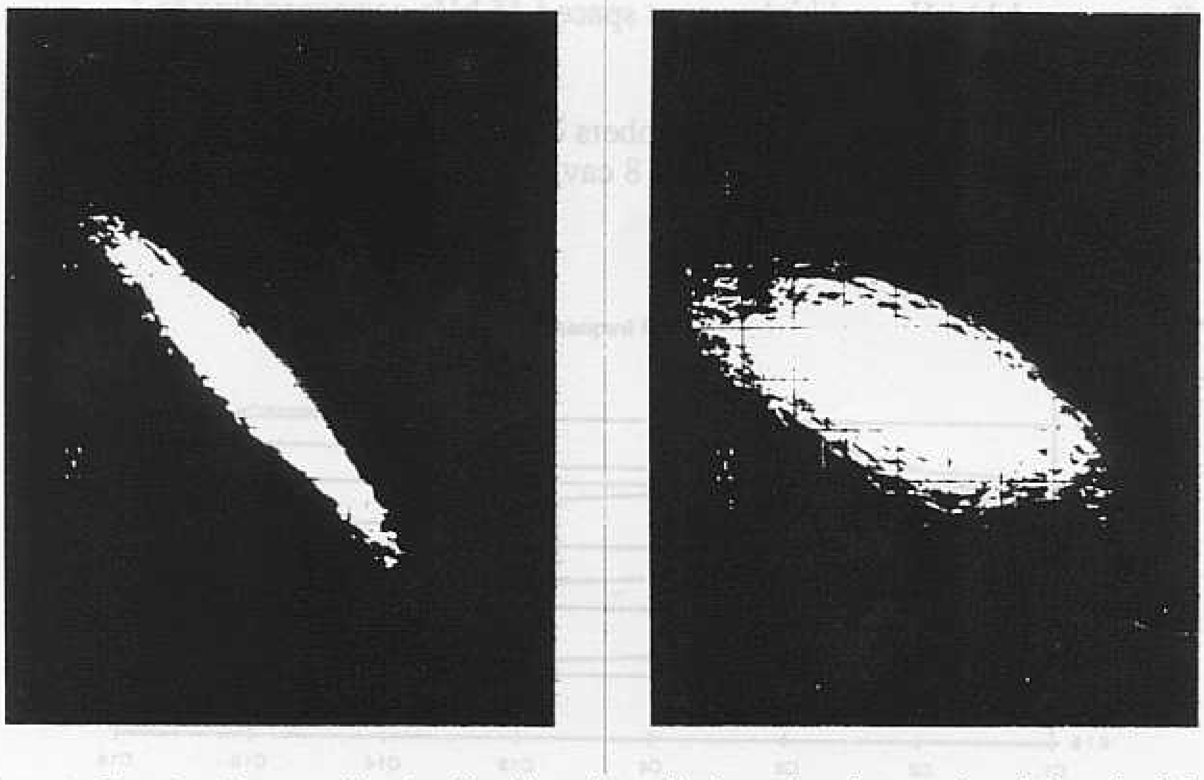

Figure 7: Lissajou figures of longitudinal bunch oscillations, bunches no. 1 and 2 to the left, bunches no. 1 and 3 to the right.

Appendix

Higher order mode measurements were done on the 8 superconducting cavities presently installed in LEP, numbered 1-4 and 13-16. A spectrum analyser and 3 wideband rf power meters were available.

Spectra

Higher order mode spectra and powers were measured in the rf units with about 50 to 100 m of coaxial cable between the cavities and the instrumentation. The spectra are corrected by the frequency dependent attenuation of the cables and the power meter readings can then be corrected by the ratio of the integrated corrected and uncorrected spectra.

An (uncorrected) spectrum of cavity 3 between 300 and 1500 MHz is shown in fig 1. The dominant contribution comes from the TM 011 mode passband at around 640 MHz.

Figs 2 to 5 show the spectra of cavity 2 around this mode with 4 single bunches and with 4 bunch trains of 3 bunchlets each. Note the "beat" pattern with peaks at 11 kHz distance and small peaks in between them. Fig 6 shows a narrow sweep (4 bunch trains with 3 bunchlets each) with lines spaced 11 kHz and higher ones spaced 45 kHz corresponding to 4 bunches.

In fig 7 the frequencies of the 4 members of the 640 MHz TM011 mode passband excited by the beam in the 8 cavities is shown. Table 1 gives the values.

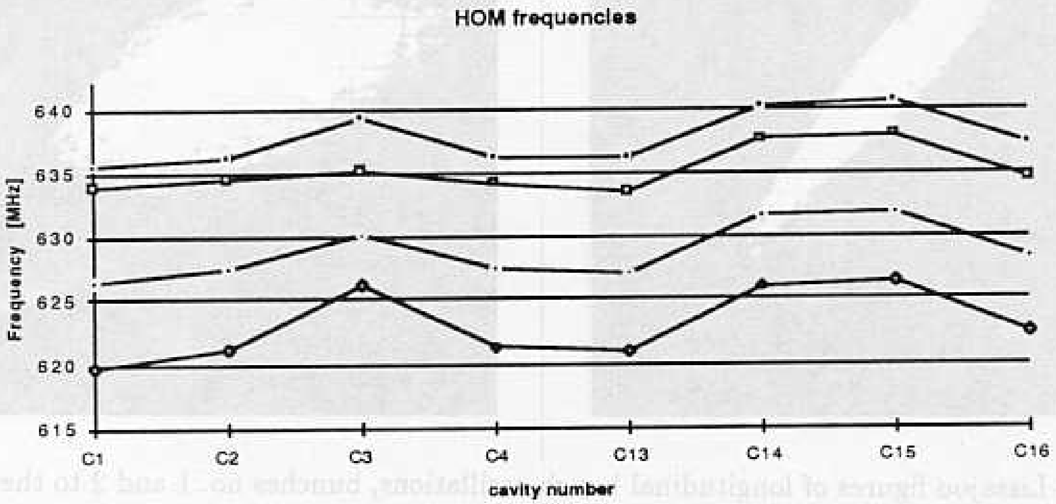

Fig 7 : frequencies of TM011 passband excited by beam.

HOM frequencies [MHZ] of TM 011 mode

C1	C2	C3	C4	C13	C14	C15	C16
635.5	636.3	639.3	636.2	636.3	640.1	640.5	637.3
633.9	634.4	635.1	634.3	633.6	637.6	637.9	634.5
626.4	627.5	630.1	627.4	627.1	631.6	631.9	628.3
619.8	621.2	626.2	621.4	621.0	626.1	626.4	622.5

Table 1 :frequencies of TM011 passband

The fundamental frequency of the cavities was not tuned to it's correct value, however the maximum tuning range for the TM010 mode is only 50 kHz. The influence on the TM011 mode is not yet measured.

HOM power

Table 2 and fig 8 give the corrected measured HOM powers for several bunch currents for 3 bunchlets per train. For comparison a measurement with single bunches is also included.

	no trains	4 trains of 3	4 trains of 3	4 trains of 3	4 trains of 3
	Power [W]	Power [W]	Power [W]	Power [W]	Power [W]
cavity nr	I_{total}=2 mA	I_{total}=3.6 mA	I_{total}=1.2mA	I_{total}=2.4 mA	I_{total}=3.6 mA
1	6.1	2.1	0.3	1.0	2.0
2	5.6	4.4	0.6	2.0	4.1
3	7.4	12.8	1.8	5.2	10.9
4	4.3	3.0	0.4	1.4	2.8
13	6.7	5.1	0.7	2.5	4.9
14	5.9	7.7	1.0	3.9	7.7
15	4.1	5.0	0.6	2.4	4.8
16	6.2	8.1	1.1	4.2	8.1
P coh	4.9	15.8	1.8	7.0	15.8
P Incoh		5.3	0.6	2.3	5.3

Table 2 : Corrected HOM powers. The total power per cavity is 4 times the indicated value, because there are 4 couplers per cavity and each coupler has 2 rf absorbers. The last 2 rows give the power per cable expected for the two extreme cases of coherent addition of fields and of incoherent addition (with loss factor of 0.22 V/pC).

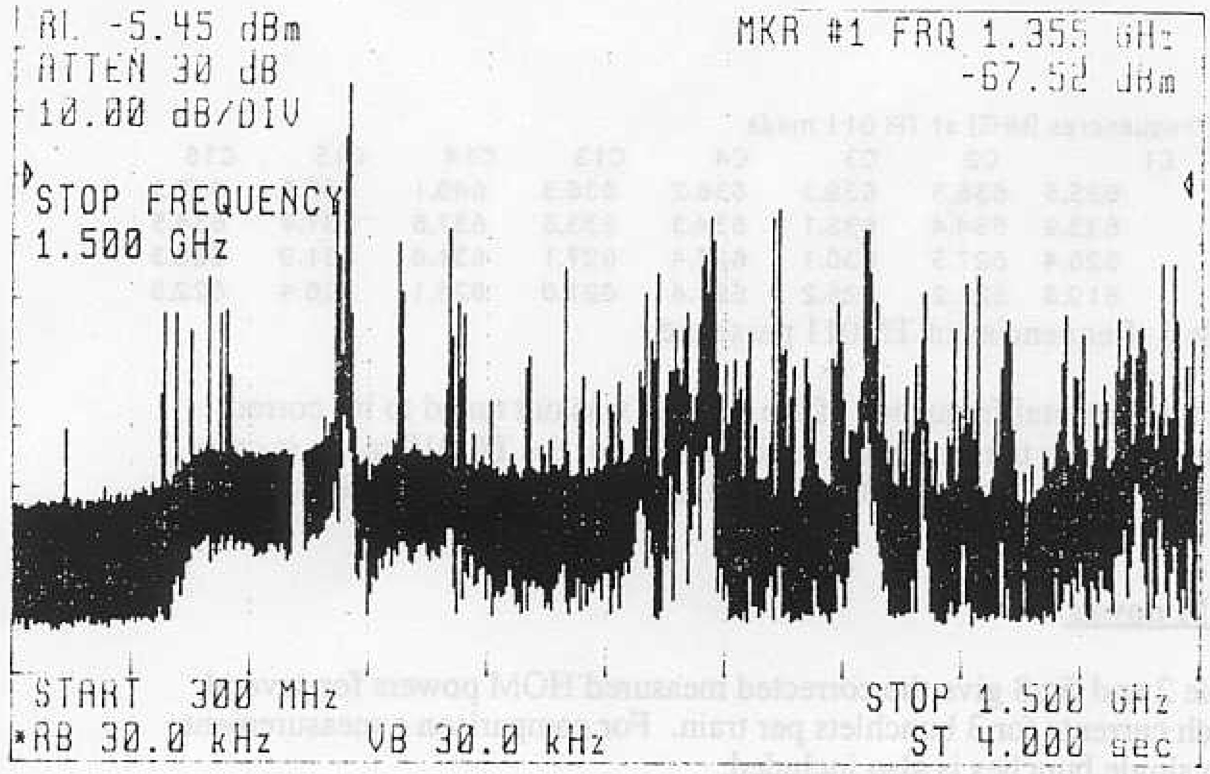

Fig. 1 HOM spectrum from 300 - 1500 MHz

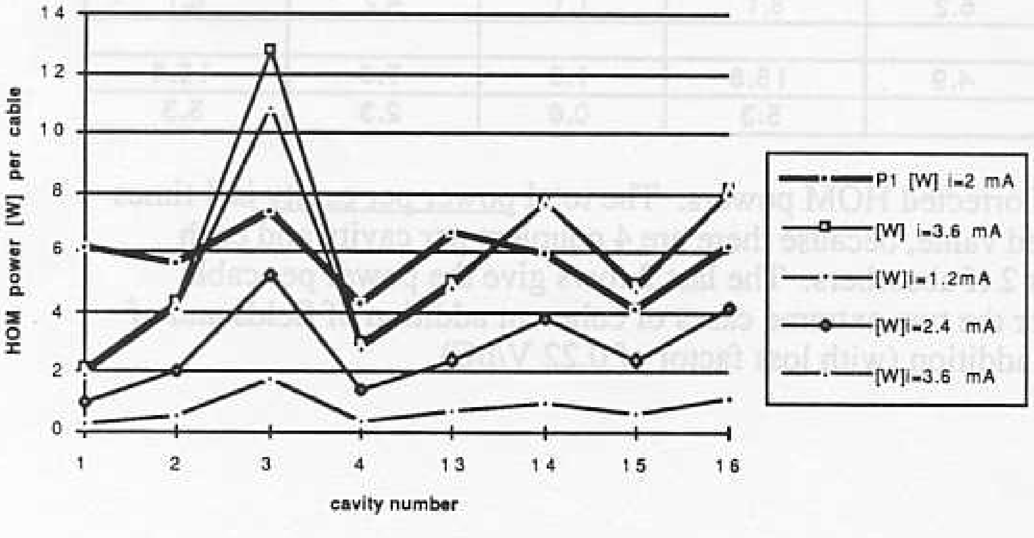

Fig 8: Corrected HOM powers per cable. The thick line is the measurement with four bunches, without bunchtrains.

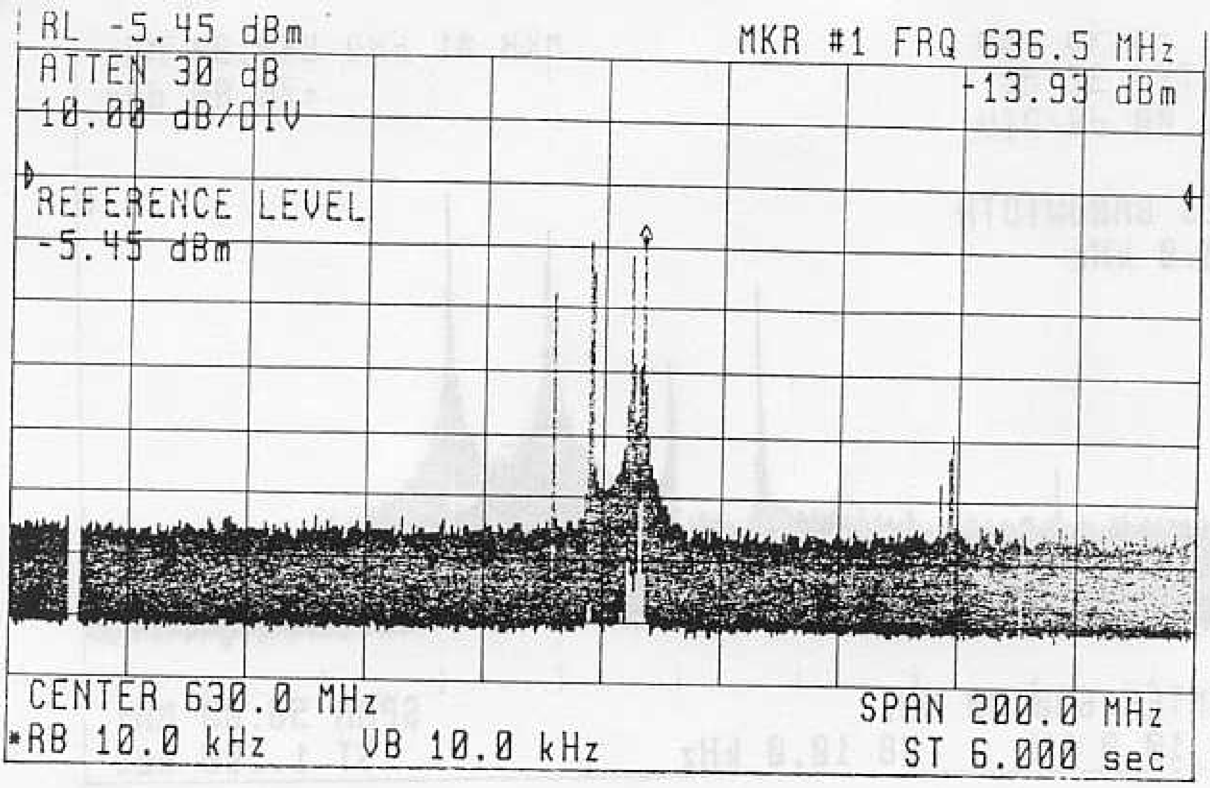

Fig 2 HOM spectrum without bunchtrains
(4 bunches one beam)

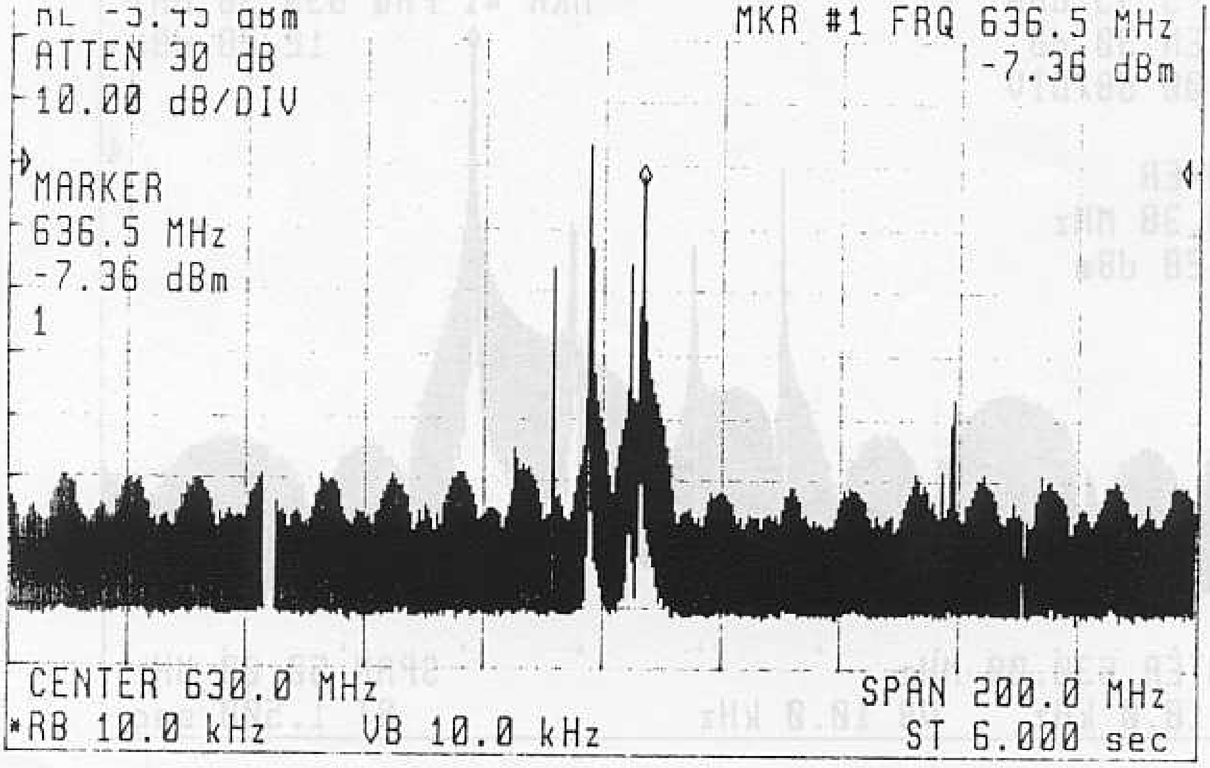

Fig 3 HOM spectrum with 4 bunchtrains,

3 bunchlets / train.

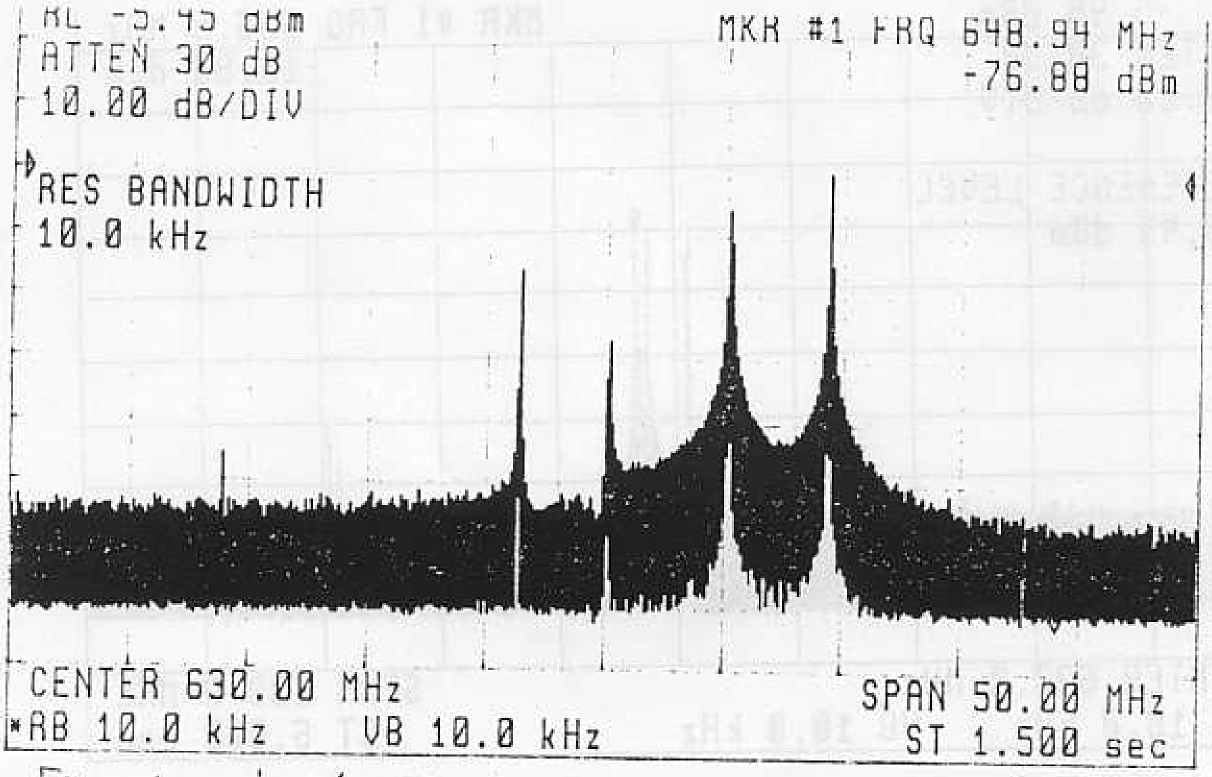

Fig 4 Mode spectrum around TM 011 mode
no bunchtrains

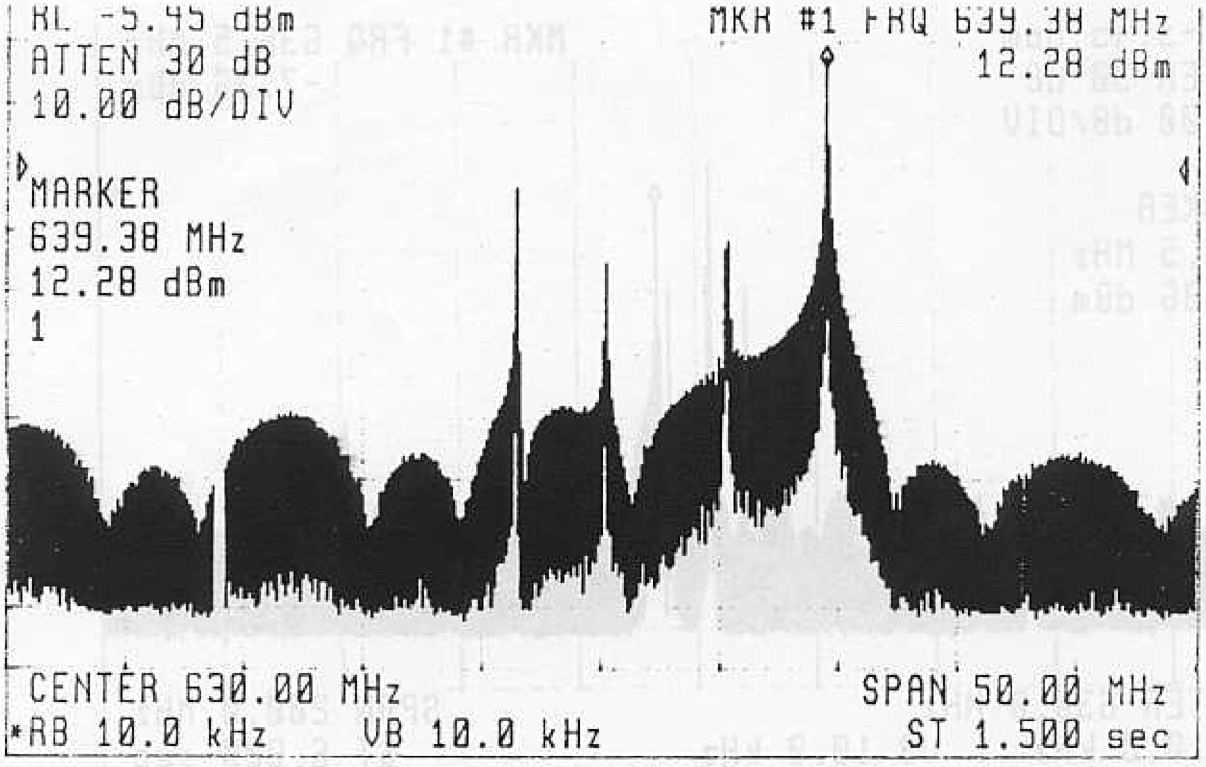

Fig 5. Mode spectrum around TM 011 mode,
4 bunchtrains (3 bunchlets)

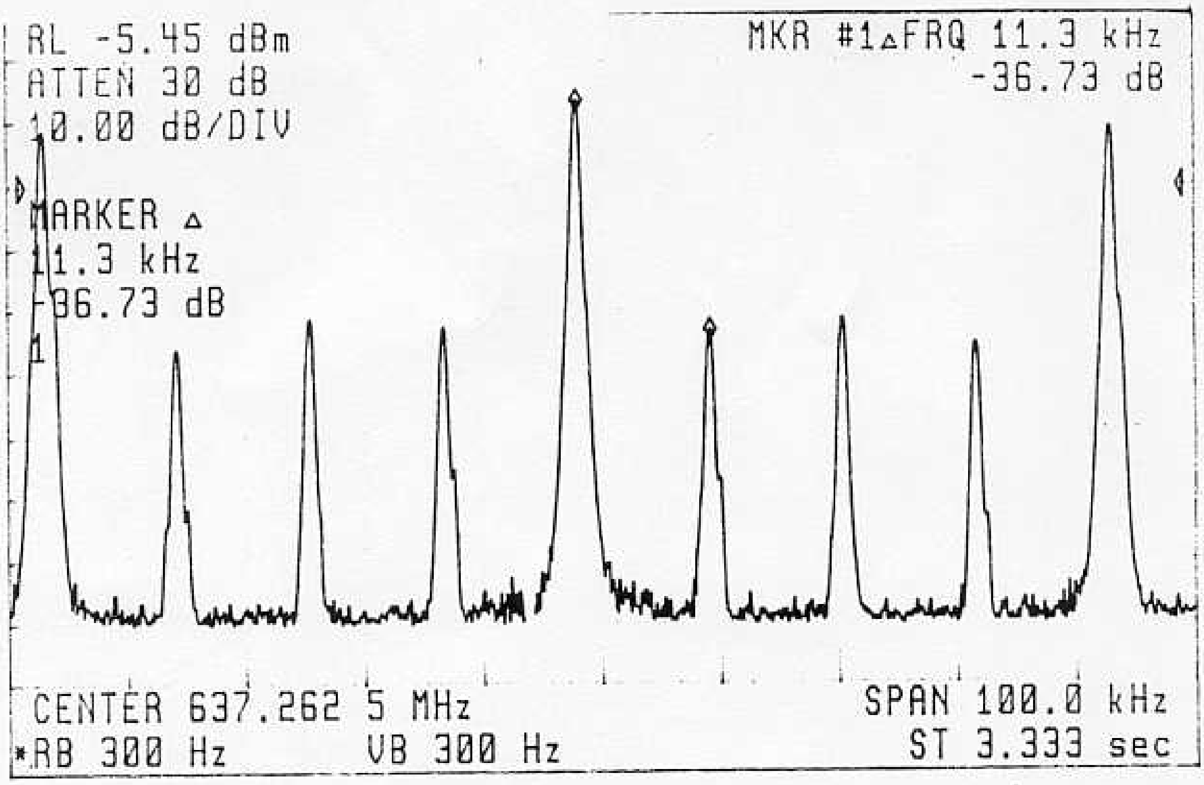

Fig 6 High resolution spectrum,
4 bunch trains