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Establishing a Kicker Gap in the PS for Extraction of LHC Beam

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1. Introduction

The PS will send bunched beam to the SPS for the LHC. The beam will be bunched on harmonic number 84 (40 MHz), but the rise time of the extraction kicker cannot be fast enough to rise cleanly between two bunches if the bunch spacing is only 25 ns. For this reason it is desirable to have three or four missing bunches in the PS at extraction time. It is undesirable to allow beam in the kicker during its rise time for three reasons: 1. lost intensity, 2. increased irradiation of machine components, 3. some fraction of the bunches may survive all the way to the LHC but will be of odd intensity and emittance. This report describes a method of establishing a gap in the bunch train before the beam is de-bunched on harmonic number 16, and maintaining that gap while the beam is then re-bunched on harmonic number 84. The technical feasibility is examined in light of using the existing PS rf cavities and power amplifiers. The intention is not to provide a definitive engineering design but to set the scale of the problem and provide an analytical approach which can serve as a framework for a particular design.

2. Concept

The method proceeds in two steps. First, a gap is created in the spacing of the 16 bunches at the end of the acceleration cycle, before de-bunching begins. Second, a barrier bucket is raised in the gap which prevents beam from migrating into the gap as the bunches are slowly de-bunched into one long continuous pulse of beam, occupying about 345 degrees of ring azimuth, but leaving 15 degrees de-void of beam. When the beam is re-bunched on harmonic number 84 there is only 80 bunches. The four-bunch gap is ample time for the kicker to cleanly extract all the beam.

The waveforms of the rf cavities that perform these manipulations are unusual in that they are not strictly periodic at the bunch frequency, even though they are periodic at the beam revolution frequency. The waveform for the first step is of the type proposed by Boussard [1] for fixed-frequency acceleration of heavy ions in the SPS. For the barrier bucket the single isolated sinewave [2] is used.

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2.1 Opening a gap

To open the gap while the beam is still held in harmonic 16 buckets the harmonic number is slowly and *continuously* changed from16 to 17. Because the process is adiabatic the bunches stay confined to their local buckets. However, when the bunch frequency is not an integer harmonic of the revolution frequency the voltage waveform has to "do a trick" in the interval between the 16th and the 1st bunch. The trick is to switch to a different frequency in this interval, such that the voltage is periodic at the revolution frequency. This provides that the phase of the rf voltage at the bunches is the same value on each turn, so the voltage still acts coherently on the bunches.

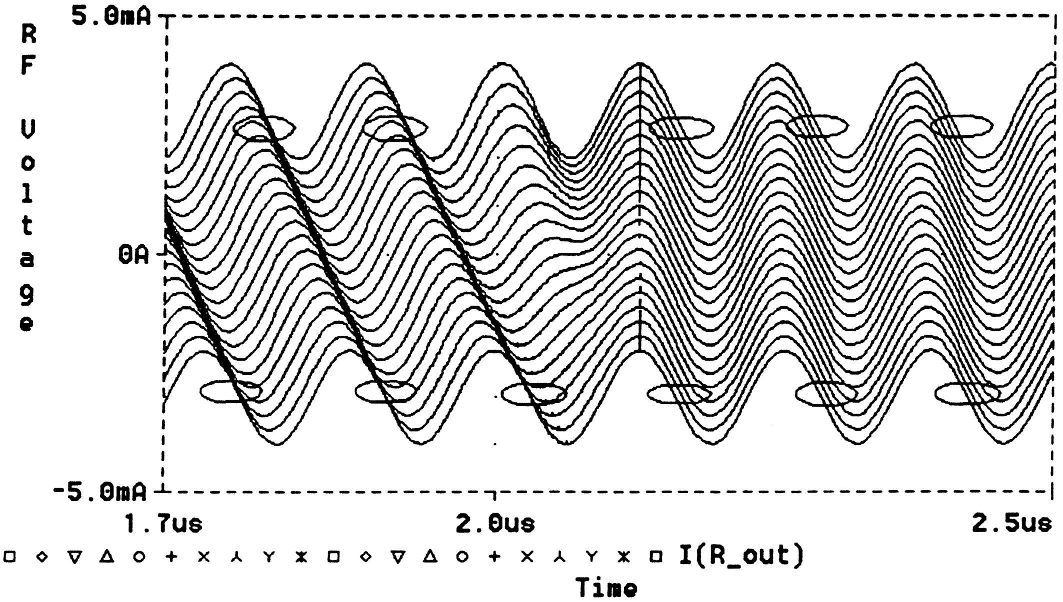


Figure 1. RF waveform for continuously changing harmonic number . The ellipses indicate stable bunch positions. Time proceeds from bottom to top.

Figure 1 illustrates this idea. At the bottom line the rf waveform is the usual h=16 form. As time progress (toward the top) the *local* rf frequency at the bunches is increased toward h=17. To provide that the voltage is synchronous with the bunch revolution frequency the waveform is modified between the 16th and the first bunch, in such a way that at the voltage is correct at bunch one. In the beginning π phase is added. At the end of the process 3π is added, since this produces, finally, a normal h=17 waveform. This progression from π to 3π is advantageous for the high level RF equipment.

The advantage comes from reducing the stress on the rf power amplifiers that have to produce this special waveform. The cavities must be tuned to the bunch frequency in order to minimize the average power. Therefore, when the frequency is switched either above or below the bunch frequency the power amplifiers must diver large current into the miss-tuned load. Furthermore, the power amplifiers are much more able to sink current than to source it. So the current available for the bipolar pulse needed for the 3π segments is much less than for the π segment. This effect sets the limit on the magnitude of rf voltage available for the beam manipulation. When the harmonic number reaches 17 then the waveform is again periodic at the bunch frequency and power amplifiers drive well matched loads.

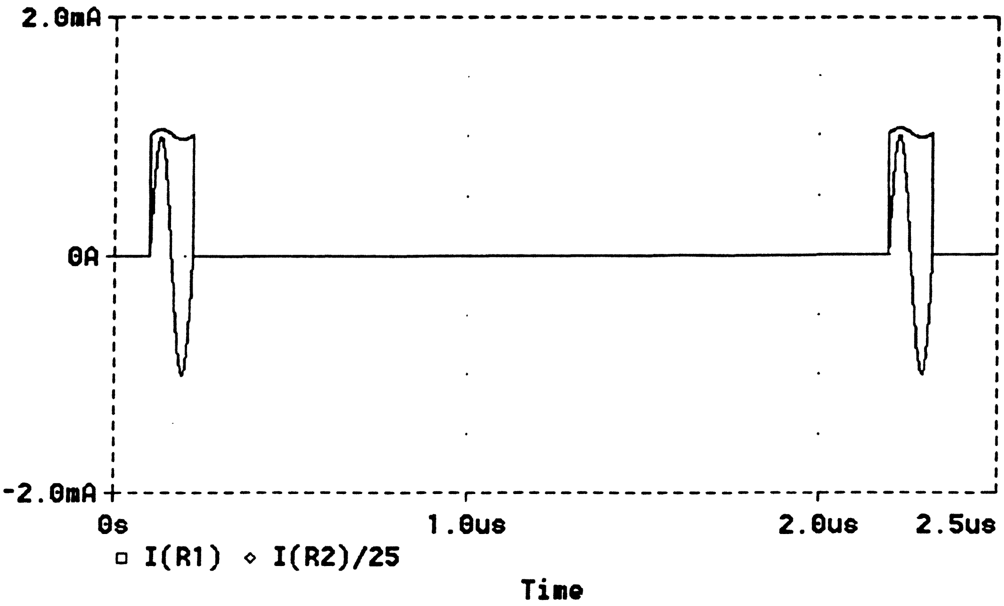


Figure 2. The barrier bucket waveform. Also shown is the idea current in the cavity to produce such a isolated sinewave. The step value of the current is I = ωCV.

2.2 The barrier bucket

The missing bunch provides the space for a barrier bucket. This barrier is created by producing a single sinewave of rf voltage each revolution period.[3] Figure 2 shows such a waveform. Just as an rf wave of the appropriate phase can attract, or capture beam, a wave of opposite phase will repel beam to effect a barrier. To de-bunch the beam the h=17 voltage will be slowly reduced until the bucket height equal the energy spread in the beam. The voltage is then switched off to allow the time structure of the beam to filament away.[4] When the barrier voltage is present the beam cannot penetrate the barrier and so particles "bounce off" the barrier, with no energy change, and continue to fill out the region of the ring not excluded by the barrier. The de-bunching process is essentially unaffected by the barrier, except that a gap remains. The beam can then be captured on h=84 in the standard way, except that only 80 buckets will have beam.

In principle, a barrier could be installed between two h=16 bunches before de-bunching, but this has disadvantages. The bunches next to the barrier will find distorted buckets from the superposition of the barrier and the h=16 voltage. This would lead to filamentation and unequal bunch populations when the beam is re-bunched on h=84. Also the barrier pulse would have to be quite short. Since the energy height of the barrier is proportional to the integral of the voltage, a short barrier requires high voltage.

3. Technical Considerations

The rf waveforms required for these operations are unusual. To find the limits of voltage possible from the existing high level rf system of the PS, a model of the power stage has been employed to simulate the behavior when making these waveforms. The first step is to model a "machine" that generates the waveforms, and the second step is to simulate the behavior the power amplifier when it is asked to produce such. The first step is essentially a first approximation to the low-level rf system. The second step uses a model of the power tetrode that represents the manufacturer's constant current characteristics.[5] PSpice is used to carry out the calculations.

3.1 Low-level signal generation

The waveforms shown in Fig. 1 are composed of three sinusoids;

$$V_f(t) = A\ \mathrm{Sin}[(16+f)\omega_0 t \tag{1}$$

$$V_{\delta 1}(t) = A\ \mathrm{Sin}[\delta 1\omega_0(t-t_1) - \pi/2 \tag{2}$$

$$V_{\delta 3}(t) = A\ \mathrm{Sin}[\delta 3\omega_0(t-t_1) - \pi/2 \tag{3}$$

Where: f goes from 0 to 1 as the harmonic number changes from 16 to 17,
ω_0 is the angular revolution frequency,
$\delta 1$ is the low offset frequency for the time between bunch 16 and one,
$\delta 3$ is the high offset frequency for the time between bunch 16 and one,
t_1 is the time of switching to the offset frequency. It corresponds to 90 degrees of phase after the center of bunch 16.

The two frequencies $\delta 1$ and $\delta 3$ must generate just the right amount of phase to smoothly connect the two ends of the offset region. It extends from 90 degrees after bunch 16 to 90 degrees before bunch one. The voltage must go from -A to +A. When the frequency is $\delta 1$ this is one half-period. When the frequency is $\delta 3$ this is three half-periods. When f is small, $\delta 1$ matches bunch frequency, and when f is close to one, $\delta 3$ matches the bunch frequency. The two frequencies are given by;

$$\delta 1 = (16 + f)/ (1 + 2f \tag{4}$$

$$\delta 3 = 3\ \delta 1. \tag{5}$$

The time to switch from $V_f(t)$ to $V_{\delta_n}(t)$ is t_1, given by;

$$t_1 = 63/(16 + f) *\pi/2\omega_0. \tag{6}$$

The time to switch from $V_{\delta_n}(t)$ back to $V_f(t)$ is t_2, given by;

$$t_2 = [(65 + 4f)/(16 + f)] * \pi/2\omega_0. \tag{7}$$

To make the transition from $\delta 1$ to $\delta 3$ smoothly, a superposition of the two signals is used, with a weighting factor that depends on f, and favors the $\delta 1$ signal.

$$V_{\delta 1+\delta 3}\ (t) = (1 - f^2)\ V_{\delta 1}(t) + (f^2)\ V_{\delta 3}(t) \tag{8}$$

This mixing of the two frequencies in the transition from δ1 to δ3 is a big help for the power amplifier. The reason is that $V_{\delta_3}(t)$ is bipolar and the tetrode of the power amplifier is much more capable of sinking current than sourcing it. So by deferring the time when the power amplifier has to produce a $V_{\delta_3}(t)$-like signal until the frequency is closer to pure harmonic 17 a high voltage can be obtained.

3.2 Block Diagram of RF Synthesizers

The waveform for the rf can be obtained from Direct Digital Synthesizers, which assure phase continuity at the switch points between the two frequency regions. By using synthesizers with dual frequency registers the delta f region can be as short as 50 ns. Figure 3 shows a block diagram of a possible implementation. A DDS such as the STEL -1375 has two frequency registers intended for frequency hopping applications. This allows very fast switching between the two frequency regions, $(16+f)\omega_0$ and either $\delta 1\omega_0$ (DDS1) or $\delta 3\omega_0$ (DDS2). The triggers to change from registers a to b come from the carry bit of the phase accumulators. Sixteen cycles of frequency a causes a switch to frequency b. While 180 degrees (DDS1) or 540 degrees (DDS2) of frequency b causes the flip back to register a. The quantity f would come from a simple counter of a clock and ranges from zero to one.

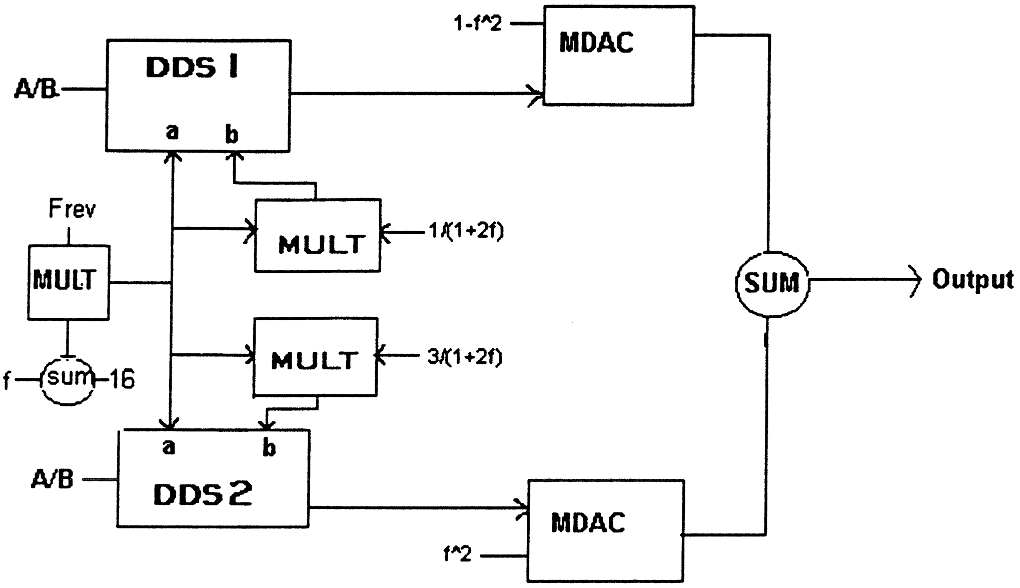


Figure 3. Block diagram for generating waveforms shown in Fig. 1. The Direct Digital Synthesizers (DDS) employ frequency hopping registers, a and b. Triggers A/B derive form phase carry bits of the numerically controlled oscillators. MDAC refers to a Multiplying digital-to-analog converter.

3.3.1 Calculations of amplifier current (harmonic changing)

The required current has been calculated using PSpice to solve for the anode current of the power amplifier tetrode in response to the waveform of Fig. 1. Details of the calculation can be found in the appendix. The result is illustrated in figure 4, which shows the anode current in the transition region when 2 kV are produced at the gap of a typical PS cavity. Each line is a solution for a different value of the parameter f, in the range 0 to 1. At about f = 0.7 the peak current of 60 amps occurs. This is within the capability of the power tetrode (Siemens RS1084CJ, 70 kW), and one must recall that the duty factor for this current is essentially one part in 17, keeping the average power reasonable.

The current was found by modeling a perfect feedback loop around the power amplifier and apply the signal shown in figure 1 as the reference input. The feedback assured that the gap voltage followed the reference input and automatically created the necessary grid voltage to produce the current from the tetrode required by the cavity.

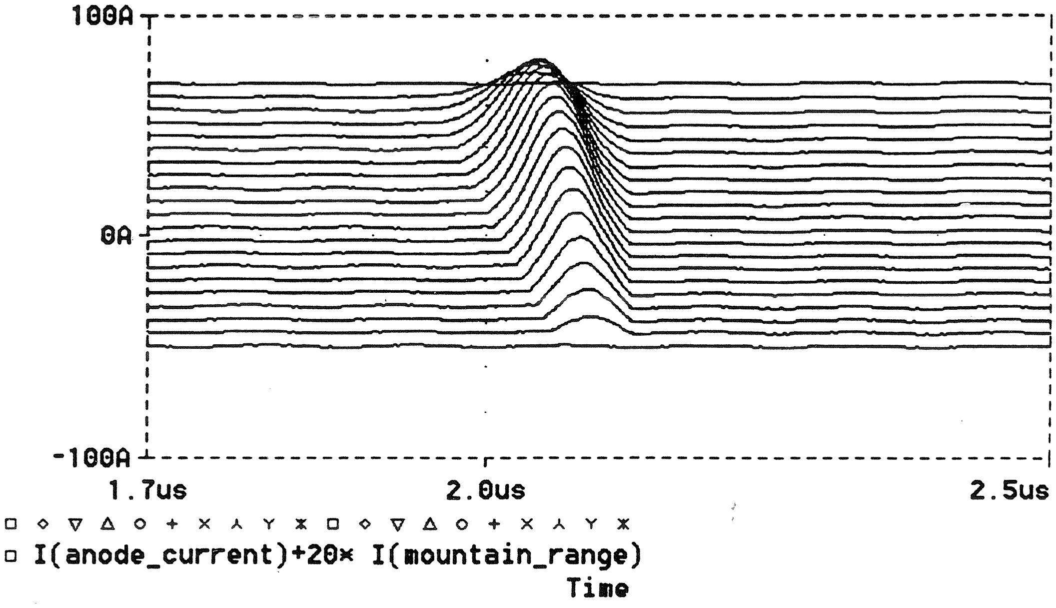


Figure 4. Current required form power amplifier for various values of parameter f. Maximum current is 50 Amps. When f = 0 or 1 the current is 0.5 Amp.

3.3.2 Calculations of amplifier current (barrier bucket)

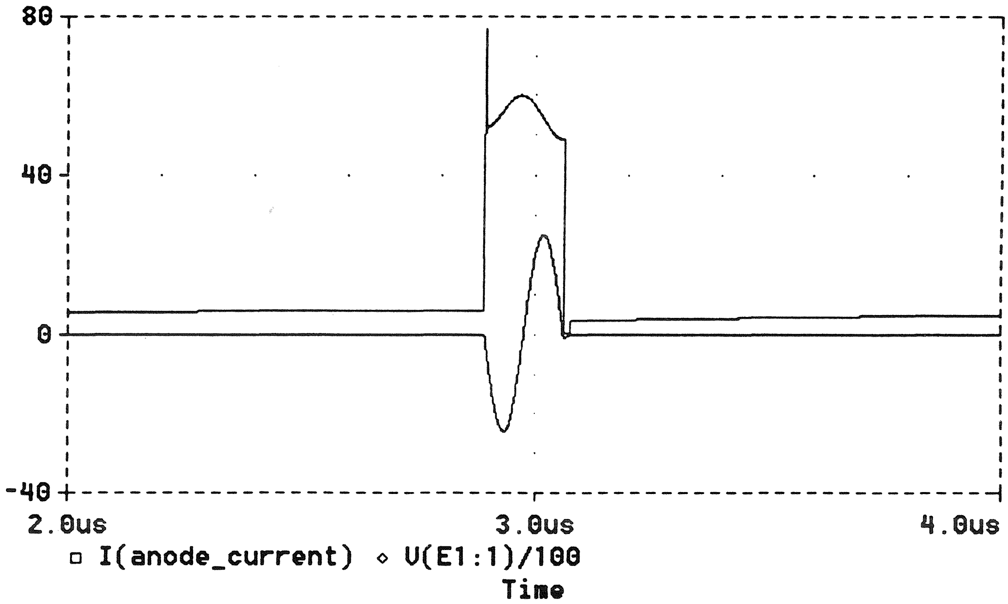


Figure 5. Calculation of the power amplifier current for 5 kV peak barrier cavity. Top trace is the anode current. A maximum value of 60 amps is required. Bottom trace is the voltage on one gap, divided by 100.

The PSpice calculation of the anode current for a 5.9 MHz barrier sine wave is shown in Fig. 5. The peak voltage of 2.5 kV per gap (two gaps per cavity) is the maximum assumed in the beam dynamics calculation described below. The polarity shown is correct for a barrier above transition. Because the power tube drives the upstream side of the gap the voltage seen by the beam is the same as used in the calculation. The tetrode is able to sink the 60 amps of current needed. If the opposite polarity were called for, for example below transition, the barrier would not be possible.

4. Simulation by Particle Tracking

The barrier is not a brick wall. The edges of the gap are somewhat "soft", and particles can migrate into the gap, in proportion to their energy deviation. The means that the debunch and recapture gymnastics at the edges of the gap are complicated. This makes it difficult to specify the minimum required voltage for the barrier. To examine the details of the debunch and recapture process a particle tracking calculation has been carried out. The program used is a special purpose code, "hardwired" for this application. Particle phases and energies are updated turn by turn and the cavity voltages can follow smooth programs for debunching and capture or rapid changes for non-adiabatic action.

For the slow voltage change for debunching and capture the standard form is used, It keeps the rate of change of fractional bucket area proportional to the inverse of the instantaneous synchrotron period. The time dependence of the amplitude is given by;

$$V(t) = Vi/\{1-x(t)[1-\mathrm{sqrt}(Vi/Vf)]\}^2 \tag{9}$$

Where: Vi is the initial voltage
Vf is the final voltage
x(t) goes from zero to one during the episode.

For the fast changes, when one of the voltages is zero, a linear interpolation is used.

The tracking begins at 26 GeV in the PS when the 16 bunches of 1.0 eVs have been taken to harmonic number 17 at 40 kV per turn. Centered at the missing bunch is the single sinewave whose frequency and amplitude can be varied. The polarity is made appropriate for barrier action by assigning a negative amplitude. The scenario proposed by Garoby [4] is followed except for the missing bunch and the barrier. The cavity amplitudes, as a function of time are shown in Fig. 6.

The cavity voltage program for the particle tracking calculation starts at the point where the beam harmonic has been changed to 17 with the missing bunch. From zero to 40 ms the harmonic 17 cavity is on, and ranges from 40 to 1 kV. From 40 ms to 80 ms only the barrier cavity is on at 5 kV. From 80 ms to 100 ms the harmonic 84 cavity switches on and ranges from 30 to 100 kV. The barrier cavity ramps down linearly to zero in this interval. At 100 ms the harmonic 84 voltage jumps to 300 kV for 180 μs. The harmonic 168 cavity then switches on for 110 μs at 600 kV.

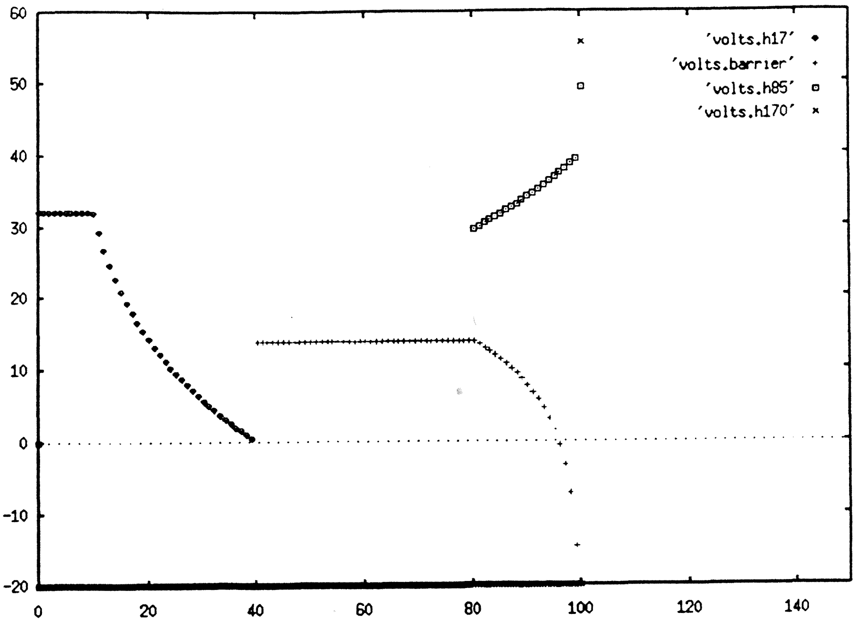


Figure 6. Cavity amplitude program. The vertical scale is cavity amplitude in dB with respect to 1 kV. The horizontal axis is time in ms.

Figure 7 shows the result of a typical run tracking 4000 particles. A barrier voltage of 5 kV peak and frequency of 6 MHz was used. Since there is no constraint between the frequency of the barrier cavity and an integer multiple of the revolution frequency, a frequency lower than the original bunch frequency is used. This requires less voltage for the barrier, and furthermore, lower frequencies for a given voltage require less current from the power amplifier. For these reasons 5 kV is used for the barrier, which could be provided by one cavity.

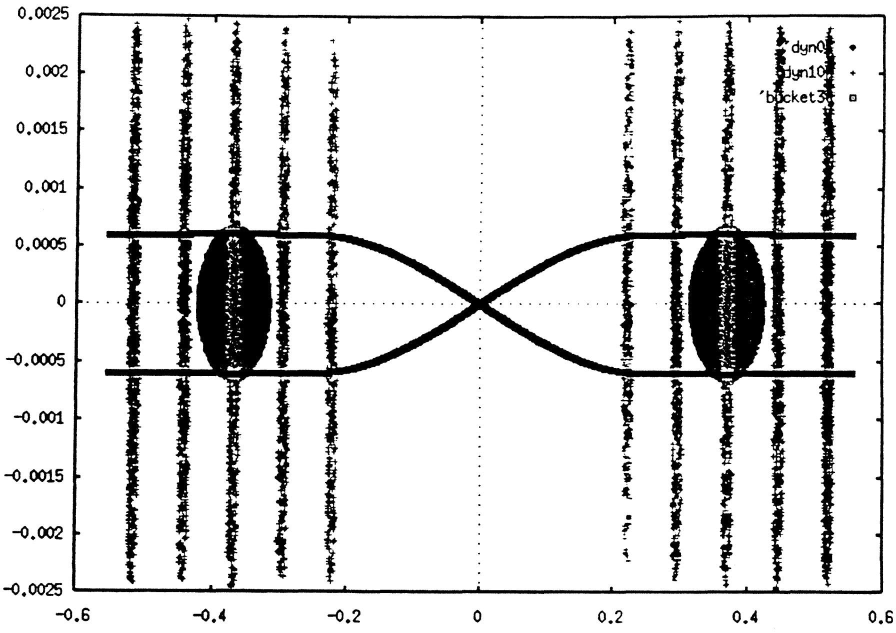


Figure 7. Results of particle tracking calculation. A gap of five missing bunches is created. The vertical scale is the fractional energy deviation of the particles. The horizontal scale is angle around the ring in radians.

During the capture on harmonic 80 particles that are originally not in the gap can be pushed into the gap by the 40 MHz voltage. Avoiding this is the reason that the barrier is left on for the beginning of the capture and ramped down linearly to zero when the 40 MHz voltage reaches 100 kV. It is likely that the same result could be obtained by ramping down faster or even switching off abruptly after a few ms.

Figure 7 shows the particle distribution at the beginning and the end of the process. The initial bunch area is 1 eVs and matched to the 40 kV bucket. The final distributions are in the combined harmonic 84 and 168 buckets. The separatrix created by the barrier cavity is included.

By projecting the particle distributions of Fig. 7 we can see an estimate of the beam current. This is shown in Fig. 8.

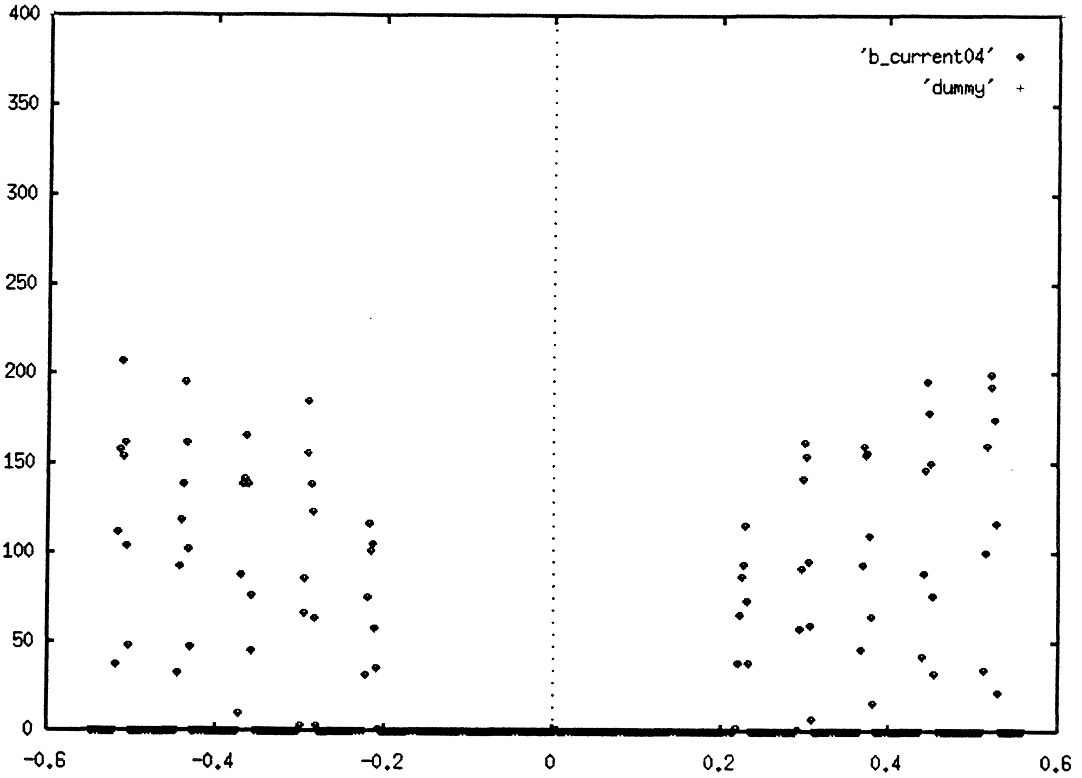


Figure 8. A projection of the particle distribution. This gives some view of the beam current. One sees that the two bunches next to the gap have somewhat reduced intensity.

5. Conclusions

It is possible to create five missing bunches when the PS beam at 26 GeV is bunched on harmonic number 84 prior to extraction to the SPS with a modest investment of hardware. The analysis done here showed that the existing high power rf equipment in the PS is capable of changing the beam harmonic number continuously from 16 to 17, thus making a missing bunch space, and then holding that space empty with a barrier bucket while the beam is debunched on harmonic 17 and re-captured on harmonic 84. It was assumed that all the cavities would participate in the harmonic changing and one cavity (the "eleventh" cavity) would provide the barrier bucket. One caution should be noted. These analysis were based on a model of the PS cavities employing an RLC circuit with 500 pF for the capacitor. A higher value of capacitance would imply proportionally lower voltages.

The question of beam loading has not been addressed here but could be significant. In particular, when the voltage is being slowly lowered on the harmonic 17 system it has been assumed that the barrier cavity has zero voltage. The significance of some beam-induced voltage on the barrier cavity should be investigated with the tracking code. It likely that some feedback will need to be applied to the barrier cavity in order to meet the requirement.

References:

1. D.Boussard, J.M. Brennan, T.P.R. Linnecar. CERN SPS/89-49 (ARF), 1989.

2. J. E. Griffin, C. Andenbrandt, J.A. MacLachlan, A. Moretti, IEEE TNS, 30, p. 3502, 1983.

3. M. Blaskiewicz, J.M. Brennan, Proceedings EPAC Sitges(Barcelona) Spain, 1996.

4. R. Garoby, PS/RF /Note 93-17, 1993

5. D. Grier, CERN PS/RF, private communication.

Appendix 1 (Tracking code)

The FORTRAN (f77) source code for the particle tracking code, acc_debun.f, is listed below. The listing is extensively annotated with comments which explain its operation. In order to make exactly five of the high frequency buckets line up with one of the h = 17 buckets the calculation actually uses harmonics 85 and 170. The small difference does not influence the conclusions from the calculations.

The input comes from two files "volt.in" and "part.in". The format of the data is explained in the listing, in the subroutines getvoltprof (profile) and getpart (particle). The output appears in three types of ASCII files; dyn* is pairs of numbers for the phase and energy deviation of each particle tracked. The files are written at each time the cavity amplitudes are specified in volt.in, and the number * is incremented. The files bucket* are the separatrices at each time the dyn* files are written. The files volts.h17, volts.barrier, volts.h85, and volts.h170 are the amplitudes of the four rf voltages. They are written each 100 beam revolutions.

A sample of the volt.in data file is:

```
11                              ; number of times amplitudes are specified, mtimes
10.5882,14.5882,2.11764,1.0588  ; half-periods of rf voltages, in degrees on whole ring, # 2,barrier
40   -0.0   0.0 0.0 0           ; amplitudes, 1,2,3,4, then time in millseconds
40   -0.0   0.0 0.0 10
1    -0.0   0.0 0.0 40
 0.0 -5.0   0.0 0.0 40.01       ; barrier gets negative sign
 0.0 -5.0   0.0 0.0 80
 0.0 -5.0  30   0.0 80.01
 0.0 -0.0 100   0.0 100
 0.0 -0.0 300   0.0 100.02
 0.0 -0.0 300   0.0 100.19
 0.0 -0.0 300 600   100.20
 0.0 -0.0 300 600   100.31
```

A sample of the part.in data file is:

```
26 628.319 6.08 1 1  ;gamma, circumference, gammaTr, charge, mass number
5.98 4000            ; bunch length in degrees on ring, number of particles <10000
```

```
      program acc_debun.f
c
c  This program is a modified version of Mike Blaskiewicz's
c program, which he wrote for simulating barrier bucket gymnastics
c in the Brookhaven AGS.  It has been changed to simulate the de-bunching/
c re-bunching in the PS for the LHC beam. It starts with two bunches
c on harmonic number 17 with a missing bunch between them. The missing
c bunch is created by the Squeeze operation. The simulation follows
c the procedure outlined by Garoby in PS/RF/Note 93-17,
c except that there is a barrier bucket in the beam gap of the missing bunch.
c  There are several things that are "hardwired" for this problem. For
```

```
c example, the harmonic number 17 is used several places, such as, creating
c the initial distribution and in calculating bucket separatrices.
c
c first get the voltage profile
      call getvoltprof
c next the initial particle properties
      call getpart
c update the system
      call update
      stop
      end
c--------------------------------------------------
      subroutine update
      parameter(pi=3.1415926536)
      parameter(npmax=10000)
      parameter(clight=2.998e8)
      parameter(mtime = 100)
      parameter(ncav = 10)
      common/particle/delta(npmax),phi(npmax),b_current(1024),npart
      common/dynamics/omega0,etotdq,beta,eta,nupdate
      common/cavprop/deftimes(mtime),amp(ncav,mtime),
     : center(ncav,mtime),wsin(ncav),mtim,ampm(10),v_time(5,1024)
      fcoeff = 1/etotdq
      pcoeff = -2*pi*eta/beta**2
      trev = 2*pi/omega0
c      write(6,*)nupdate ,'=nupdate, nturns/write'
c      read(5,*)nforwrite
      nforwrite = nupdate/100
      nwritten = 0
c
c  loop over the number of turns in time specified, write voltages
c  every "nforwrite" turns, update phase and energy each turn,
c  write output files, dyn*, at times specified at deftimes(k)
c
      ivolt=1
      tk=0.
      do k0=0,nupdate
        ntest = k0/nforwrite
        ntest = ntest*nforwrite
        t_now = k0*trev
        if(abs(t_now-deftimes(nwritten+1)).lt.trev) then
c
          call writit(k0,nwritten)
          nwritten = nwritten+1
        endif
        if(ntest.eq.k0.and. ivolt.lt.1000)then
          dummy=0.
          call getvolt(tk,dummy,voltage)
          v_time(1,ivolt) = -20
          if(abs(ampm(1)).gt.0.1)then
          v_time(1,ivolt) = 20*log10(abs(ampm(1)))
          endif
          v_time(2,ivolt) = -20.
          if(abs(ampm(2)).gt.0.1)then
          v_time(2,ivolt) = 20.*log10(abs(ampm(2)))
          endif
          v_time(3,ivolt) = -20.
          if(abs(ampm(3)).gt.0.1)then
          v_time(3,ivolt) = 20.*log10(abs(ampm(3)))
```

```
          endif
          v_time(4,ivolt) = -20.
          if(abs(ampm(4)).gt.0.1)then
          v_time(4,ivolt) = 20.*log10(abs(ampm(4)))
          endif
          v_time(5,ivolt) = tk*1000.
          ivolt=ivolt+1
          endif
        do k = 1,npart
          phk = phi(k)
          deltak = delta(k)
c calculate the cavity passage time for this particle
c on this turn
          tk = k0*trev - phk/omega0
c get the voltage in kV
          call getvolt(tk,phk,voltage)
          deltak = deltak + voltage*fcoeff
          delta(k)= deltak

          phk = phk + pcoeff*deltak
c
c  for the PS problem we limit the calculation to three h=17
c  periods, with the barrier in the middle,empty bucket
c
c put in -range to +range
c
          range =2.* pi/17. + 0.5*2.*pi/17.
          if(phk.gt.rnage) phk = phk - 2.*range
          if(phk.lt.-range) phk = phk + 2.*range

c          if(phk.gt.pi)phk = phk-2*pi
c          if(phk.lt.-pi)phk = phk + 2*pi
          phi(k) = phk
        enddo
      enddo
c
c  write the file "volts.***" to show voltage time profile
c
      open(unit=20,file='volts.h17',status='unknown')
      do iv0=1,ivolt
        write(20,*) v_time(5,iv0),v_time(1,iv0)
        enddo
        close(20)
      open(unit=20,file='volts.barrier',status='unknown')
      do iv0=1,ivolt
        write(20,*) v_time(5,iv0),v_time(2,iv0)
        enddo
        close(20)
      open(unit=20,file='volts.h85',status='unknown')
      do iv0=1,ivolt
        write(20,*) v_time(5,iv0),v_time(3,iv0)
        enddo
        close(20)
      open(unit=20,file='volts.h170',status='unknown')
      do iv0=1,ivolt
        write(20,*) v_time(5,iv0),v_time(4,iv0)
        enddo
        close(20)
c
```

```
c  Here we sum up the number of particles at each phase angle,
c  to give a representation of the beam current each bunch
c
      do ib0=1,1023
       b_current(ib0)=0.
       enddo
       do ib=1,npart
        t = phi(ib)*256./((3*2*pi)/17./2.)
        it = int(t) + 256
        if(it.gt.0.and.it.lt.513) then
         b_current(it) = b_current(it) + 1
         endif
         enddo
         open(unit=20,file='b_current',status='unknown')
         do ib_out=1,512
          t_out = ib_out*(3.*2*pi/17./2.)/256. - 0.55
          write(20,*) t_out,b_current(ib_out)
          enddo
          close(20)
      call writit(nupdate,nwritten)
      return
      end
c----------------------------------------
      subroutine getvoltprof

      parameter(pi=3.1415926536)
      parameter(mtime = 100)
      parameter(ncav = 10)
      common/cavprop/deftimes(mtime),amp(ncav,mtime),
     :  center(ncav,mtime),wsin(ncav),mtim,ampm(ncav),v_time(5,1024)
      open(unit=20,file='volt.in',status='unknown')
c  The number of times at which
c  the waveforms are defined (linear interpolation between '
      read(20,*) mtim
c assume four sin-like waveforms, read their half widths in
c degrees of phase (0 -> 360) around ring
c cavity number two is the barrier, it has one single period,
c the amplitude should be negative to make a barrier.
c
      read(20,*)wsin(1),wsin(2),wsin(3),wsin(4)
      do iwsin=1,ncav
      wsin(iwsin) = wsin(iwsin)*pi/180.
      enddo
c read their amps (in kV) at the mtim readtimes. The times in ms at
c which the amplitudes are given  =deftimes(k).
      do k=1,mtim
       read(20,*)amp(1,k),amp(2,k),amp(3,k),amp(4,k),
     :          deftimes(k)
       deftimes(k) = deftimes(k)/1000.
      enddo
      close(20)
      return
      end
c-----------------------------------------------------------------
      subroutine getpart
      parameter(npmax=10000)
      parameter(clight=2.998e8)
      parameter(pi=3.1415926536)
      parameter(mtime = 100)
```

```
      parameter(ncav = 10)
      common/cavprop/deftimes(mtime),amp(ncav,mtime),
     : center(ncav,mtime),wsin(ncav),mtim,ampm(ncav),v_time(5,1024)
      common/particle/delta(npmax),phi(npmax),b_current(1024),npart
      common/dynamics/omega0,etotdq,beta,eta,nupdate
      real v0(npmax)
c calculate initial particle positions
      open(unit=20,file='part.in',status='unknown')
c get the Lorentz factor, ring circumference, transition gamma
c number of protons per nuclei and mass of nuclei in amu
      read(20,*)gamma,circ,gammat,zpart,apart
      partmass = apart*931481.2 !keV
      etotdq = gamma*partmass/zpart !kV
      beta = sqrt(1-1/gamma**2)
      vel = beta*clight
      trev = circ/vel
      write(6,*)trev,'seconds = revolution period '
      omega0 = 2*pi/trev
      eta = 1/gammat**2 - 1/gamma**2
      nupdate = deftimes(mtim)/trev


c
c     This is specific for the cern PS (LHC) debunch calculation,
c     always have two bunches, on harmonic 17
c     read in; bunch length[degrees on the ring],
c     and Number of particles in each bunch
c
      read(20,*) bl,Num_part
      bl = bl*(pi/180.)
c
      npart = 1
      spacing = bl/(Num_part/2.)
c  this is the spacing between particles within the bunch
c
      phi_center = (-360./17.)*(pi/180.)
      eV=amp(1,1)
      eh = sqrt(beta**2*eV/(pi*17.*abs(eta)*etotdq))
c
      do k1 = 1,2
c    two bunches only, h = 17
c
        phi_part = phi_center - bl/2.
        p_1 = phi_part*17. + pi
c
        do k2 = 1, Num_part/2
c
          ph_k = (phi_part)*17. + pi

          e = eh * SQRT(abs(cos(p_1)-cos(ph_k)))
c
          call random_number(r)
          r=2.*(r-.5)
          e = e*r
          phi(npart)    = phi_part
          delta(npart)  = e
          delta(npart+1) = -e
          phi(npart+1)  = phi_part
c
```

```
          npart = npart + 2
          phi_part = phi_part + spacing
c
          enddo
        phi_center = phi_center + (360./17.)*(pi/180.)*2.
          enddo
      close(20)
      return
      end
c----------------------------------------------------------------
      subroutine getvolt(t0,phk,voltage)
c the timing assumes that the particle phase is not confined
c between 0 and 2*pi (eg the actual time can be quite
c different for different particles
      parameter(mtime = 100)
      parameter(ncav = 10)
      parameter(pi=3.1415926536)
      common/cavprop/deftimes(mtime),amp(ncav,mtime),
     : center(ncav,mtime),wsin(ncav),mtim,ampm(ncav),v_time(5,1024)
c phk is azimuthal position in the rotating frame
      if(deftimes(1).ge.t0)then
        m1 = 1
        m2 = 1
        x = 0
        go to 45
      endif
      do k=2,mtim
        tk = deftimes(k)
        if(tk.gt.t0)then
           m1 = k -1
           m2 = k
           x = (tk - t0)/(tk - deftimes(k-1))
           go to 45
        endif
      enddo
      m1 = mtim
      m2 = mtim
      x = 0
45    continue
      sum = 0
      do mm=1,4
c  here we assume four cavities, number two is the barrier
c
        v_1=amp(mm,m1)
        v_2=amp(mm,m2)
        if(abs(v_1).lt.001.or.abs(v_2).lt.001) then
c
c  if one of the voltages is zero (<.001) then make linear interpolation
c
        ampm(mm) = x*amp(mm,m1) + (1-x)*amp(mm,m2)
        go to 50
        endif
c
c  if changing between two levels, then use adabatic law
c
        ampm(mm)=v_1/(1.-(1.-x)*(1.-sqrt(abs(v_1/v_2))))**2
50      continue
c
        width=wsin(mm)
```

```
         arg = phk
         call fsin(force,arg,width,mm)
         sum = sum + ampm(mm)*force
        enddo
        voltage = sum
        return
        end
c-----------------------------------------------------------------
c
c this subroutine is not used, but could be used to try square
c pulse-shape barrier
c
      subroutine fsquare(force,arg,width)
      test = abs(arg)
      if(test.gt.3.1416)write(6,*)' arg off'
      force = 0
      if(test.lt.width)then
        if(arg.gt.0)force= 1
        if(arg.lt.0)force=-1
      endif
      return
      end
c----------------------------------------------------
      subroutine fsin(force,arg,width,mm)
      parameter(pi=3.1415926536)
      test = abs(arg)
      force = 0.0
c
c  mm equals two is the barrier, single sinewave
c
      if(test.lt.width .or. mm.eq.1.or.mm.eq.3.or.mm.eq.4)then
        force= sin(pi*arg/width)
      endif
      return
      end

c--------------------------------------------------------------------
      subroutine writit(ntime,nwritten)
      parameter(npmax=10000)
      parameter(clight=2.998e8)
      parameter(pi=3.1415926536)
      parameter(mtime = 100)
      parameter(ncav = 10)
      common/cavprop/deftimes(mtime),amp(ncav,mtime),
     :  center(ncav,mtime),wsin(ncav),mtim,ampm(ncav),v_time(5,1024)
      common/particle/delta(npmax),phi(npmax),b_current(1024),npart
      common/dynamics/omega0,etotdq,beta,eta,nupdate
      real v0(npmax),volts(npmax)
      character*20 outfile
c
c  Note that harmonic 17 is assumed here for const
c
      const=beta**2/(pi*17.*abs(eta)*etotdq)
      if(nwritten.lt.10)then
        write(outfile,2000)nwritten
      else
        write(outfile,2001)nwritten
      endif
2000  format('dyn',i1)
```

```
2001  format('dyn',i2)
      open(unit=21,file=outfile,status='unknown')
      open(unit=20,file='dyn',status='unknown')
      do k=1,npart
        write(20,*)phi(k),delta(k)
        write(21,*)phi(k),delta(k)
      enddo
      close(20)
c get the potential energy
      t0 = ntime*2*pi/omega0
      sum = 0
      npt = 1440
c      dphi = 2*pi/npt
      dphi = (2.*pi/17.)*3./npt
      do k=1,npt
        phk =-1.*(2*pi/17.)*(3./2.) +  k*dphi
c v0 is q/etot * integral of  voltage*dphi
        call getvolt(t0,phk,voltage)
c
c  the plus sign in the sum below is correct for above tansition
c
        sum = sum + voltage*dphi*17.
        volts(k) = voltage
        v0(k) = sum
      enddo
      vmin = v0(1)
      do k=2,npt
        if(v0(k).lt.vmin)vmin=v0(k)
      enddo
      do k=1,npt
        v0(k) = v0(k) + vmin
      enddo
      vmax = v0(1)
      do k=2,npt
        if(v0(k).gt.vmax)vmax=v0(k)
      enddo
      if(nwritten.lt.10)then
        write(outfile,1000)nwritten
      else
        write(outfile,1001)nwritten
      endif
1000  format('bucket',i1)
1001  format('bucket',i2)
      open(unit=21,file=outfile,status='unknown')
      open(unit=20,file='volts',status='unknown')
      do k=1,npt
        phk =-1.*(2*pi/17.)*(3./2.) +  k*dphi
        bkt=sqrt(const*(abs(v0(k)-vmax)))
        write(20,*) phk,bkt
        write(20,*) phk,-bkt
        write(21,*) phk,bkt
        write(21,*) phk,-bkt
c         write(20,*) phk,volts(k)
c         write(21,*) phk,volts(k)
      enddo
      close(20)
      close(21)
      write(6,*)nwritten,' Files written ',npart,ntime,t0
      write(6,*)' plot files ready '
```

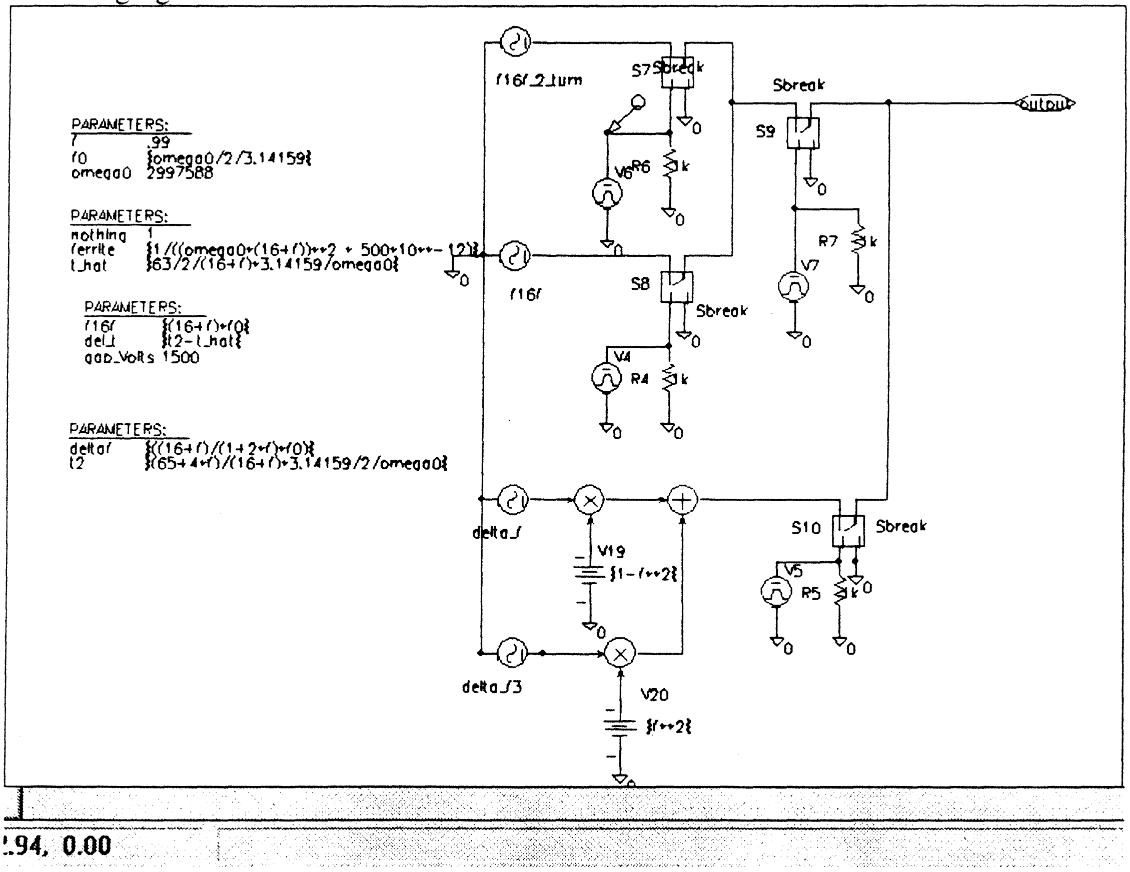
```
return
end
```

Appendix 2 (PSpice calculations)

The calculations with PSpice are in two parts. First, circuits are created to generate the waveforms, either the harmonic number change or the barrier bucket. They work with sinewave voltage sources which get switched in or out. The switches are controlled pulse generators. The frequencies, delay times and phases are controlled with parameters, such as "t_hat" etc. Then these circuits are made into special parts which are used in the model of the power amplifier and cavity.

The calculation is parameterized with the parameter "f", which specifies the frequency during the harmonic changing. See equation 1. The cavity is tuned by adjusting the inductance according to f. The inductance is made to resonate with the 500 pF of the cavity plus the 45 pF from the tetrode output capacitance. Perfect feedback is modeled so that the cavity voltage exactly follows the input voltage. In this way the PSpice is working as a digital simulation of the analog computer for the non-linear problem tetrode behavior. The result is that we find the maximum voltage for which the real tetrode could provide sufficient current. This is what is shown in figures 4 and 5.

Here is the schematic and netlist for the circuit that generates the wave form for changing harmonic 16 to 17.



PARAMETERS:
f .99
f0 {omega0/2/3.14159}
omega0 2997588

PARAMETERS:
nothing 1
ferrite {1/((omega0*(16+f))**2 * 500*10**-12)}
t_hat {63/2/(16+f)*3.14159/omega0}

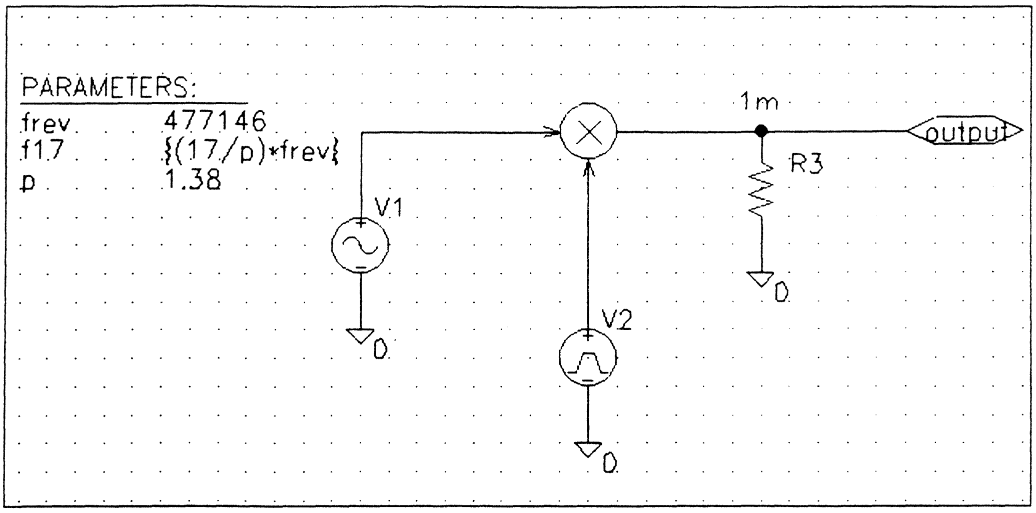
PARAMETERS:
f16f {(16+f)*f0}
del_t {t2-t_hat}
gap_Volts 1500

PARAMETERS:
deltaf {((16+f)/(1+2*f)*f0)}
t2 {(65+4*f)/(16+f)*3.14159/2/omega0}

* Schematics Netlist *

```
V_f16f_2_turn      $N_0001 0
+SIN 0 1 {f16f} {t2} 0 90
V_f16f      $N_0002 0
+SIN 0 1 {f16f} 0 0 0
V_delta_f      $N_0003 0
+SIN 0 1 {deltaf} {t_hat} 0 -90
S_S7      $N_0001 $N_0005 $N_0004 0 Sbreak
RS_S7      $N_0004 0 1G
S_S8      $N_0002 $N_0005 $N_0006 0 Sbreak
RS_S8      $N_0006 0 1G
S_S9      $N_0005 $N_0008 $N_0007 0 Sbreak
RS_S9      $N_0007 0 1G
S_S10      $N_0010 $N_0008 $N_0009 0 Sbreak
RS_S10      $N_0009 0 1G
V_V4      $N_0006 0
+PULSE 1 0 {t2} .1n .1n 10u 100u
V_V5      $N_0009 0
+PULSE 0 1 {t_hat} .1n .1n {del_t} 100u
V_V7      $N_0007 0
+PULSE 1 0 {t_hat} .1n .1n {del_t} 100u
R_R6      0 $N_0004  1k
R_R4      0 $N_0006  1k
R_R5      0 $N_0009  1k
R_R7      0 $N_0007  1k
V_V6      $N_0004 0
+PULSE 0 1 {t2} .1n .1n 10u 100u
V_V15      $N_0011 $N_0008 {m_range}
R_R_out      $N_0011 0  1k
V_delta_f3      $N_0012 0
+SIN 0 1 {deltaf*3} {t_hat} 0 -90
E_MULT1      $N_0013 0 VALUE {V($N_0014)*V($N_0003)}
E_MULT2      $N_0015 0 VALUE {V($N_0016)*V($N_0012)}
E_SUM1      $N_0010 0 VALUE {V($N_0015)+V($N_0013)}
V_V19      $N_0014 0 {1-f**2}
V_V20      $N_0016 0 {f**2}
```

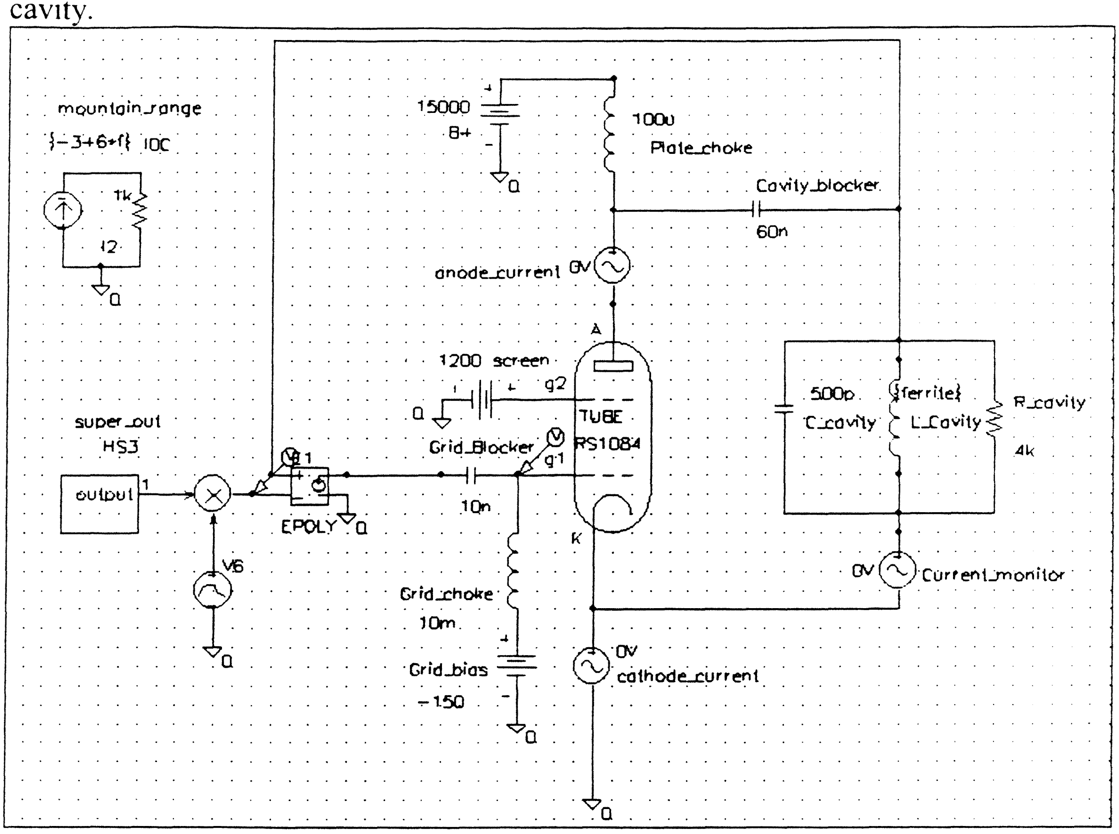
Here is the netlist for the circuit that generates the barrier cavity waveform.



* Schematics Netlist *

```
V_V1        $N_0001 0 DC 0 AC 0
+SIN 0 1 {f17} 100n 0 0
V_V2        $N_0002 0 DC 0 AC 0
+PULSE 0 1 100n 1p 1p {1/f17} {1/frev}
R_R1        $N_0003 0  1000
C_C1        $N_0003 0  500p
L_L1        $N_0003 0  {1/((6.28319*f17)**2*500*10**-12)}
E_MULT1         $N_0004 0 VALUE {V($N_0002)*V($N_0001)}
R_R2        $N_0004 $N_0003  1m
C_C2        $N_0004 $N_0003  1n
```

Here is the schematic and netlist for the circuit that models the tetrode driving the cavity.



```
* Schematics Netlist *
X_REFDES      $N_0004 $N_0002 $N_0001 $N_0003 RS1084
L_Plate_choke     $N_0005 $N_0006  100u
L_L_Cavity     $N_0007 $N_0008  {ferrite}
C_C_cavity     $N_0007 $N_0008  500p
L_Grid_choke     $N_0009 $N_0002  10m
C_Cavity_blocker     $N_0005 $N_0008  60n
R_R_cavity     $N_0008 $N_0007  4k
V_B+     $N_0006 0 15000
V_Grid_bias     $N_0009 0 -150
V_screen     $N_0003 0 1200
V_Current_monitor     $N_0007 $N_0004 DC 0V AC 0V
E_E1     $N_0011 0 POLY(1) $N_0008 $N_0010 0.0 10
V_cathode_current     $N_0004 0 DC 0V AC 0V
C_Grid_Blocker     $N_0011 $N_0002  10n
E_MULT1     $N_0010 0 VALUE {V($N_0012)*V($N_0021)}
V_V6     $N_0012 0 DC 0 AC 0
+EXP 0 1 0 600n 10u 10u
V_anode_current     $N_0005 $N_0001 DC 0V AC 0V
V_HS3_f16f_2_turn     $N_0014 0
+SIN 0 {gap_Volts} {f16f} {t2} 0 90
V_HS3_f16f     $N_0015 0
+SIN 0 {gap_Volts} {f16f} 0 0 0
V_HS3_delta_f     $N_0016 0
+SIN 0 {gap_Volts} {deltaf} {t_hat} 0 -90
S_HS3_S7     $N_0014 $N_0018 $N_0017 0 Sbreak
RS_HS3_S7     $N_0017 0 1G
S_HS3_S8     $N_0015 $N_0018 $N_0019 0 Sbreak
RS_HS3_S8     $N_0019 0 1G
S_HS3_S9     $N_0018 $N_0021 $N_0020 0 Sbreak
```

```
RS_HS3_S9        $N_0020 0 1G
S_HS3_S10        $N_0023 $N_0021 $N_0022 0 Sbreak
RS_HS3_S10        $N_0022 0 1G
V_HS3_V4        $N_0019 0
+PULSE 1 0 {t2} .1n .1n 10u 100u
V_HS3_V5        $N_0022 0
+PULSE 0 1 {t_hat} .1n .1n {del_t} 100u
V_HS3_V7        $N_0020 0
+PULSE 1 0 {t_hat} .1n .1n {del_t} 100u
R_HS3_R6        0 $N_0017  1k
R_HS3_R4        0 $N_0019  1k
R_HS3_R5        0 $N_0022  1k
R_HS3_R7        0 $N_0020  1k
V_HS3_V6        $N_0017 0
+PULSE 0 1 {t2} .1n .1n 10u 100u
V_HS3_delta_f3        $N_0024 0
+SIN 0 {gap_Volts} {deltaf*3} {t_hat} 0 -90
E_HS3_MULT1        $N_0025 0 VALUE {V($N_0026)*V($N_0016)}
E_HS3_MULT2        $N_0027 0 VALUE {V($N_0028)*V($N_0024)}
E_HS3_SUM1        $N_0023 0 VALUE {V($N_0027)+V($N_0025)}
V_HS3_V19        $N_0026 0 {1-f**2}
V_HS3_V20        $N_0028 0 {f**2}
I_I2        0 $N_0013 DC {-3+6*f}
R_mountain_range        $N_0013 0  1k
```