A CONSOLE PROGRAM FOR EXAMINING BEAM CAPTURE IN STATIONARY BOOSTER BUCKETS

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Introduction

This work concerns itself with the evolution of the booster proton beam during the first few hundred turns following injection.[1,2] During this period the rf accelerating voltage must be turned on in such a way as to accomplish optimum "adiabatic capture" of the injected beam into 30 MHz "buckets". Also, during this period, the 200 MHz linac bunch structure must fold itself into the 30 MHz "buckets" in some innocuous way.

If the booster accelerating cavities are all turned on at a sufficiently low gap voltage to cause good adiabatic capture, it is known that some of the cavities will suffer from electron multipactoring, subsequently inhibiting further increase in voltage. Consequently, it has been necessary to turn the cavities on individually in time sequence, each at the lowest possible voltage. An alternative procedure is to turn all of the cavities on previous to injection but with groups or pairs of cavities out of phase ("paraphased") so that the net accelerating voltage is zero. When voltage is required the cavities are brought into phase by a program which allows optimum capture.

It is apparent that these rf turn-on procedures can be done in a large variety of ways and the manner in which the beam responds to these variations is not always obvious. A study of a large class of these procedures using the booster itself would require a large amount of time and large quantities of "wasted" beam. In an effort to make such a study easier and more heuristic, a booster console access program called CAPTURE has been generated.

In this program the phase space created by one rf bucket ($-\pi$ to $+\pi$ radians) can be filled with an arbitrary number of particles with chosen momentum spread, momentum error, and linac bunching factor. A number of rf accelerating gaps between one and forty can be placed at any of 84 possible locations around the (simulated) orbit and each selected gap voltage can be given a sign, allowing pairs or groups of gaps to be placed in "paraphase". The voltages on the gaps can be selected individually so that paraphasing errors or mismatches may be introduced. The gap voltages may be held in paraphase until a specified turn at which time the gap voltages are brought into phase uniformly over a specified number of turns. All time periods in the program are cast in terms of the fundamental rotation period of the machine at injection, or "turns". Gaps which were initially positive are retarded in phase by 90 degrees while negative gaps are advanced by 90 degrees resulting in an in-phase condition. The motion of particles of the selected ensemble may be observed on each turn (or nth turn if desired) before, during, and following the "orthophasing" process.

A variation of the program allows gap voltages to be changed arbitrarily after each of several turns so that "step-wise" turn-on may also be simulated. The program presents only "stationary buckets", i.e. no net acceleration takes place and the synchronous phase angle is always zero. Particles are not "lost" during the successive calculations. If a particle leaves the phase space to the left ($-\pi$) it will re-enter at corresponding point on the right ($+\pi$). Because the calculation is done for a machine well below transition a particle will move to the left in the phase space if, because of initial conditions and subsequent acceleration, it's momentum is greater than that of a "synchronous" particle. Because its velocity exceeds that of a synchronous particle it will complete one turn in a time shorter than a synchronous period and arrive "early". Particles trapped within the bucket will, consequently, move on counter-clockwise contours in the phase space. If a particle gains energy such that it deviates from the synchronous energy by more than the full-scale plot presentation it cannot be plotted, but is is not "lost" from the calculation. There are no "real machine" aperture limitations imposed by the program although such a modification could easily be incorporated.

In addition to plotting the location of each particle in the phase space after the specified number of turns the program also plots a "profile" of the point distribution at the bottom of the page. This profile is representative of the "bunch shape" which would be observed in the machine by a broad band detector which detects the instantaneous value of the bunch current. The profile is created by dividing the 2π radius in the phase space into 50 bins and summing the number of particles in each bin. These numbers are then connected by a straight line segments. Choice of the number of bins is a compromise between the desired longitudinal resolution and statistical fluctuations within each bin due to the small total number of particles.

Details of Program Use

An example of the display page of the "CAPTURE" program is shown in Fig.1. The listing at the bottom of the page indicates that the calculation is to be started with an accelerating gap of 30 kV at location 48 and a paraphased, or cancelling gap voltage at location 49. A similar pair of paraphased gap voltages has been placed at locations 72 and 73. Additional voltages may be introduced by entering them in empty locations in similar fashion.

Gap order is not important in the list, the program will order them. If a gap number is repeated only the latter one in the list will survive.

Line 3 of the display page indicates that the first plot of particle location will be presented after calculations have been made for 100 turns.

The following lines indicate that the cavities will be held out of phase until the 10th turn and the gap voltages will be brought into phase linearly between the 10th and the 22nd turn.

```
                    02/08/77  1454

94 BUNCHING  PROFILE ADV....          OF 1K
             ITERATE STEPS..   0      TURN
* PLOT PHASE SPACE AFT...... 100      TURN
  START PARA................ 10       TURN
  END PARA..................  22      TURN
  INJ PERCENT E SPREAD +-.... .15    PER
  INJ E OFFSET(NOM200MEV)...         KEV
  NUMBER OF PARTICLES....... 400
  PLOT FULL SCALE+-.........1000     KEV
  PROFILE FULL SCALE........ 200
  BUNCHING FACTOR........... 5
0 ABORT 1 IH PRO 2 CONT 6 LIN 7 IH ERRAS
  RF GAPS PER1-84 VOLT +- PARA
  P    KEV   P    KEV   P    KEV   P    KEV
 48* 30    * 0* 0     * 0* 0     * 0* 0
 49*-30    * 0* 0     * 0* 0     * 0* 0
 72* 30    * 0* 0     * 0* 0     * 0* 0
 73*-30    * 0* 0     * 0* 0     * 0* 0
 84* 0     * 0* 0     * 0* 0     * 0* 0
  0* 0     * 0* 0     * 0* 0     * 0* 0
  0* 0     * 0* 0     * 0* 0     * 0* 0
  0* 0     * 0* 0     * 0* 0     * 0* 0
  0* 0     * 0* 0     * 0* 0     * 0* 0
  0* 0     * 0* 0     * 0* 0     * 0* 0
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Figure 1. Display Page for Booster Console Program "CAPTURE".

The injected energy spread will be ±0.5 percent. There is no average injection energy offset indicated. The number of particles being calculated is 400. The plot scale will be ±1000 KeV. If a profile of the particle distribution is plotted the scale will be 200 particles full scale and if injected linac bunching is selected the bunching factor will be 5.

With all sense switches off, an interrupt will start the basic calculation. After calculating particle locations for 100 turns a plot of particle locations will appear on a 611 and the calculation will stop. The vertical scale of the phase space plot is kinetic energy with a center value of 200 MeV.

Increasing the number of gaps, the number of turns, and the number of particles will give a product increase in the time required to calculate the plot. The computer must calculate each point through each gap on each turn. If it is desired, subsequently, to observe the distribution at a time greater than 100 turns computation time will be saved if the data for 100 turns is stored and the subsequent calculation started there rather than starting over. This can be done through the use of one of the console sense switches provided that fewer than 400 points are being calculated. This and other additional procedures may be selected by use of various of the sense switches.

Sense Switches

Switch 0: Abort switch - This stops the calculation as soon as the point being calculated is plotted. When this is done the program will probably not have completed calculation on all of the points inserted so that the table of stored data will have an inconsistent set of points in it. Therefore, after an abort the calculation should be started from the beginning to avoid an inconsistent result.

Switch 1: When each complete calculation is plotted a profile of points per bin is also plotted at the bottom of the page. This is representative of the bunch shape that would be seen by a fast detector looking at the beam current. If many successive points are plotted the profiles may superpose into a useless jumble. The profile plot may be inhibited by setting sense switch 1.

Switch 2: After calculation is complete and a plot of all points is presented the program can be restarted using the existing data by inserting a turn number on line 3 at least one unit greater than that which was calculated, setting switch 2, and interrupting. If the turn number on line 3 were increased and the calculation started without setting switch 2, the calculation would start from zero again.

The interrupt for each restart causes the previously plotted data to be erased. It is frequently useful to inhibit the plot erasure so that successive calculations are added to the existing display. This may be done using the left-most rectangular switch immediately above the sense switches. This feature is particularly useful when only a few points (perhaps 6 or 8) are introduced initially. The inhibited erasure will then yield a plot of the trajectory of these few points in the phase space. If the points are given an appropriate initial offset in energy they can be placed such that some will be captured within the bucket while others remain outside. In this way the bucket boundary for a given ring voltage can be outlined. Also one can examine other aspects of particle motion within the bucket such as the synchrotron frequency and synchrotron tune spread.

Switch 3: This is an alternative abort switch. Its use can best be understood in the context of the use of switch 5. See Switch 5 description.

Switch 4: In order to minimize computation time the initial table of gap voltages is normally read only once at the beginning of any sequence of calculations. If switch 4 is set the gap voltage table is read following each interrupt restart. This allows one to calculate phase space motion until some turn number (line 3), reset gap voltages or even add additional gaps, then compute phase motion for some additional number of turns, and continue the process. If switch 4 is set the automatic progression of phase in the paraphase process is defeated, and all gap voltages which appear in the file following an interrupt are interpreted to be in phase. Signs in the voltage table are ignored.

The purpose of this feature is to allow simulation of the step turn-on procedure for beam capture. There is no automatic or programmed procedure for changing voltages or introducing new voltages following completion of calculation, it must be done each time manually.

If it is intended to operate the program in the automatic iteration mode (switch 5) switch 4 should not be set because time will be wasted reading the same gap voltage list on each iteration.

Switch 5: The program can be made to restart automatically following completion and plotting of all points by setting switch 5. The number of turns to be calculated in each automatic iteration, i.e. between each presentation of the data, must be entered on line 2. If it is intended to start automatic iteration following initial calculation of some number of turns it will be necessary to increase the turn number on line 3 and set switch 2 to prevent the program from starting over at zero. In this mode the plot of points is not erased between iterations regardless of the setting of the "erase inhibit" button.

Switch 6: In normal operation the selected number of particles will appear initially in a uniform band with vertical heigh dictated by the selected injection energy spread. If switch 6 is set the particles will be bunched longitudinally into bands representing the 200 MHz linac bunch structure. A linac "bunching factor" must be introduced on line 11. A factor of 1 will yield a non-bunched uniform distribution. As this factor is increased the longitudinal space into which the particles are placed become narrower, i.e. for a bunching factor of 5 four-fifths of the long tudinal space will be empty and all of the particles will be plac in seven vertical bands comprising one-fifth of the longitudinal space.

Since the 200 MHz rf frequency is not an integer times the 30 MHz booster frequency the linac bunches cannot appear symmetri ally in adjacent booster phase spaces. Since this program treat only a single period of phase space and particles which leave on one side enter on the other, a slight error is introduced in part icle locations if the particles leave and re-enter the phase spac because they enter from a phase space which is not populated quit correctly with linac bunches.

Switch 7: If switch 7 is set the phase space plot will not be presented at the conclusion of a calculation, leaving only the longitudinal current profile plot. During an iterated sequence of calculations a succession of profile plots can be presented by introduction of a number in line 1 indicating the magnitude of the advance. In this way "hill and valley" displays of bunch shape evolution can be simulated.

Comments: The vertical scale which is calculated and plotted is proton kinetic energy as are the energy offset and percent energy spread. Since the linac beam is usually characterized by its momentum spread dP/P it is necessary to correct this to dT/T if it is desired to examine real linac beam effects. Since the center energy is 200 MeV

$$\frac{dT}{T} = \frac{1 + \gamma}{\gamma} \frac{dP}{P} = 1.824 \frac{dP}{P}$$

Examples: As an example of the use of iterative calculation (switch 5) Fig. 2a shows the location of four particles introduce with a kinetic energy offset of 352 KeV after one turn.

The ring voltage consists of 25 kV at location 48 and -25 kV at location 73. The voltages are brought quickly into phase between turns 2 and 3. Figure 2b shows the location of the same four points during the first 15 turns. The left-most point has departed from the area to the left and re-entered on the right. The next particle headed for the fixed point at $-\pi$ rad. and $\Delta E = 0$ but curved downward away from it while remaining within the bucket. The trajectories of the remaining two particles are clearly evident. Figure 2c shows the same population after 36 turns. The particle nearest the center of the space has complete one synchrotron revolution while the particle which narrowly missed the fixed point has completed less than half a revolution. The trajectory of the latter particle very nearly defines the phase space area separatrix. The particle which started farthest from the center of the bucket continues to drift along outside the bucket, slipping phase with those particles which are capture within the bucket. Such a particle could not be subsequently accelerated.

The bucket half-height in this representation is, for Vgap = 50 kV

$$\Delta E = \left(\frac{2\beta^2 E_3 \quad eV}{\pi h \eta} \right)^{\frac{1}{2}} = 63.8 \ (\text{gap kV})^{\frac{1}{2}}$$

$$= 451 \text{ KeV.}$$

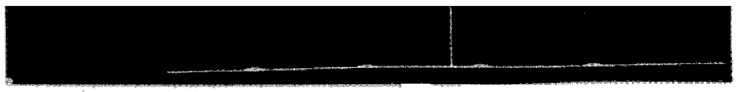
Figures 3a, b, and c show the location of one-hundred particles with an initial energy spread of 0.01 percent after 1,10, and 30 turns with a quickly established ring voltage of 60 kV. The projection at the bottom of each plot indicates that the longitudinal current in such a distribution becomes tightly bunched after ten turns then becomes diffuse again as the distribution continues to wind about itself. From this picture one can infer something about the synchrotron tune spread in this bucket and the fraction of particles whose synchrotron frequency is reasonably constant.

As a final example of the use of this program, a linac bunched beam of 400 particles with an energy spread of 0.15 percent and a bunching factor of 5 is examined. Figure 4a shows the distribution after one turn. The linac bunch structure is clearly visible both in the space population and in its projection. Four accelerating gaps of 16 kV are provided at locations 48,49,73, and 74. The voltage are initially cancelling. In figures 4b and c the populations are shown after 40 and 101 turns for the case where the rf voltage is brought into phase slowly between turns 5 and 35. It is apparent that all of the injected particles have been captured within the phase space "bucket" and the energy spread has increased to about 0.27 percent or by a factor of 1.8. Since optimum adiabatic capture should have resulted in an increase by a factor of about 1.5 the implication is that the final rf voltage of 64 kV and the paraphasing time are very nearly optimized. In Figures 4d and e the same initial distribution is shown after 40 and 105 turns for the case where the same rf gap voltages were turned on quickly between turns 5 and 6. It is clear that this rapid turn-on causes a larger energy spread and many particles are on trajectories which are outside of the bucket. The 30 turn turn-on time is close to the minimum time for acceptable capture.

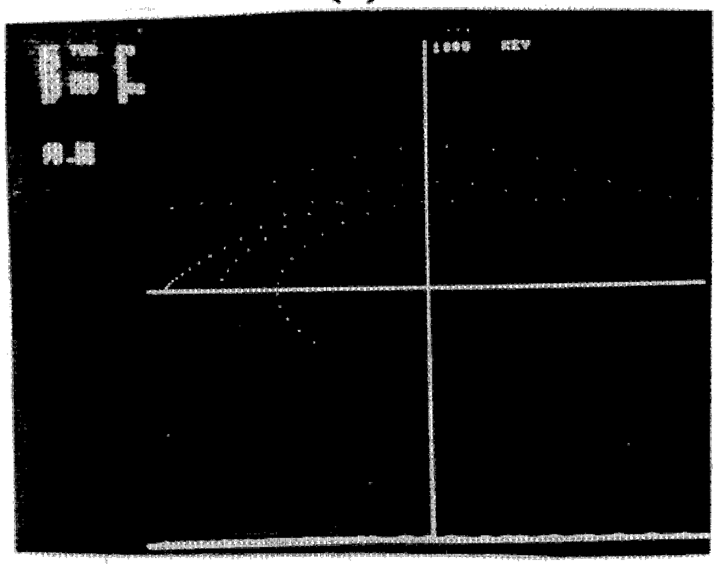
References

1. "RF Capture in the NAL Booster", J. A. MacLachlan TM-303-0330 (1971).

2. "Effects of Nonlinearities on the Phase Motion in the NAL Booster", W. W. Lee TM-333-0300 (1971).



(a)



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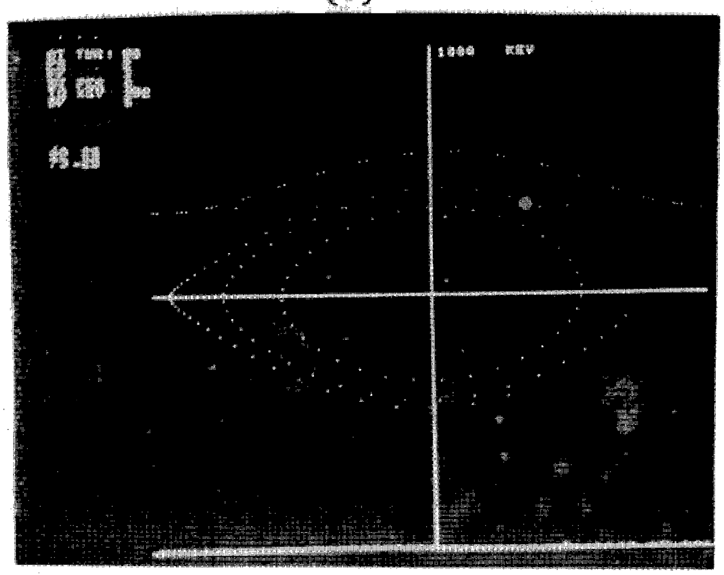
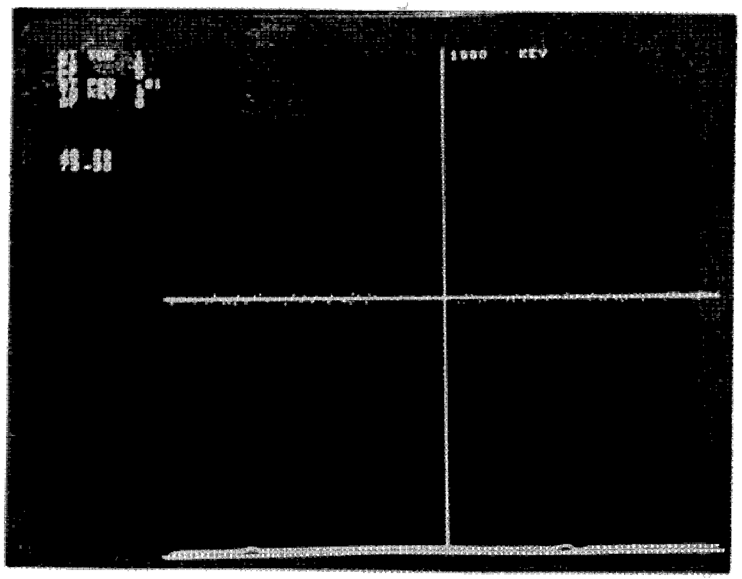
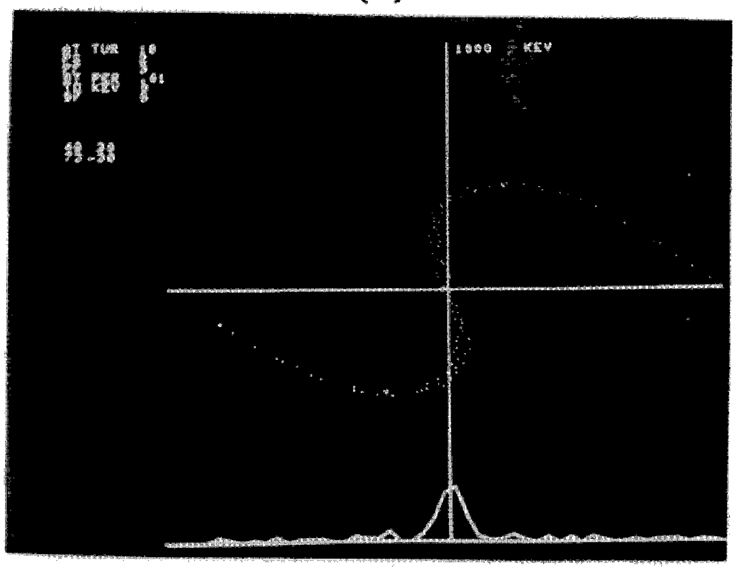


(c)

Figure 2 a) Four points offset in energy by 352 KeV
b) After 15 turns
c) After 36 turns



(a)



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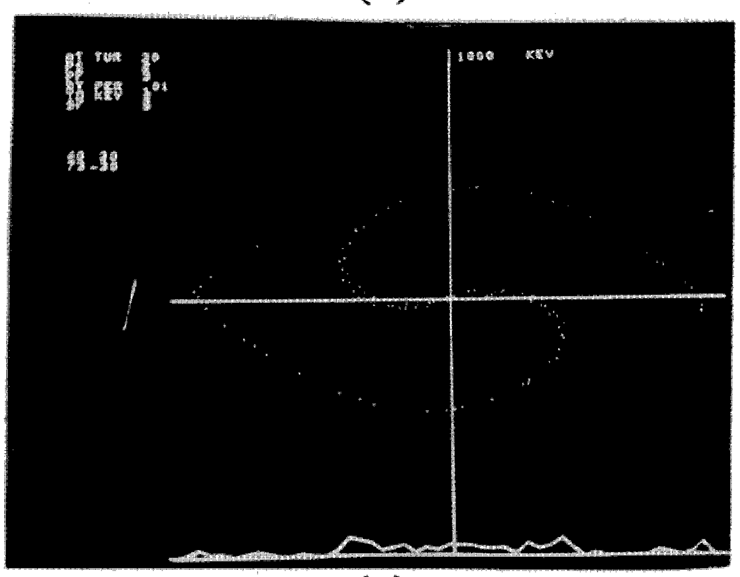
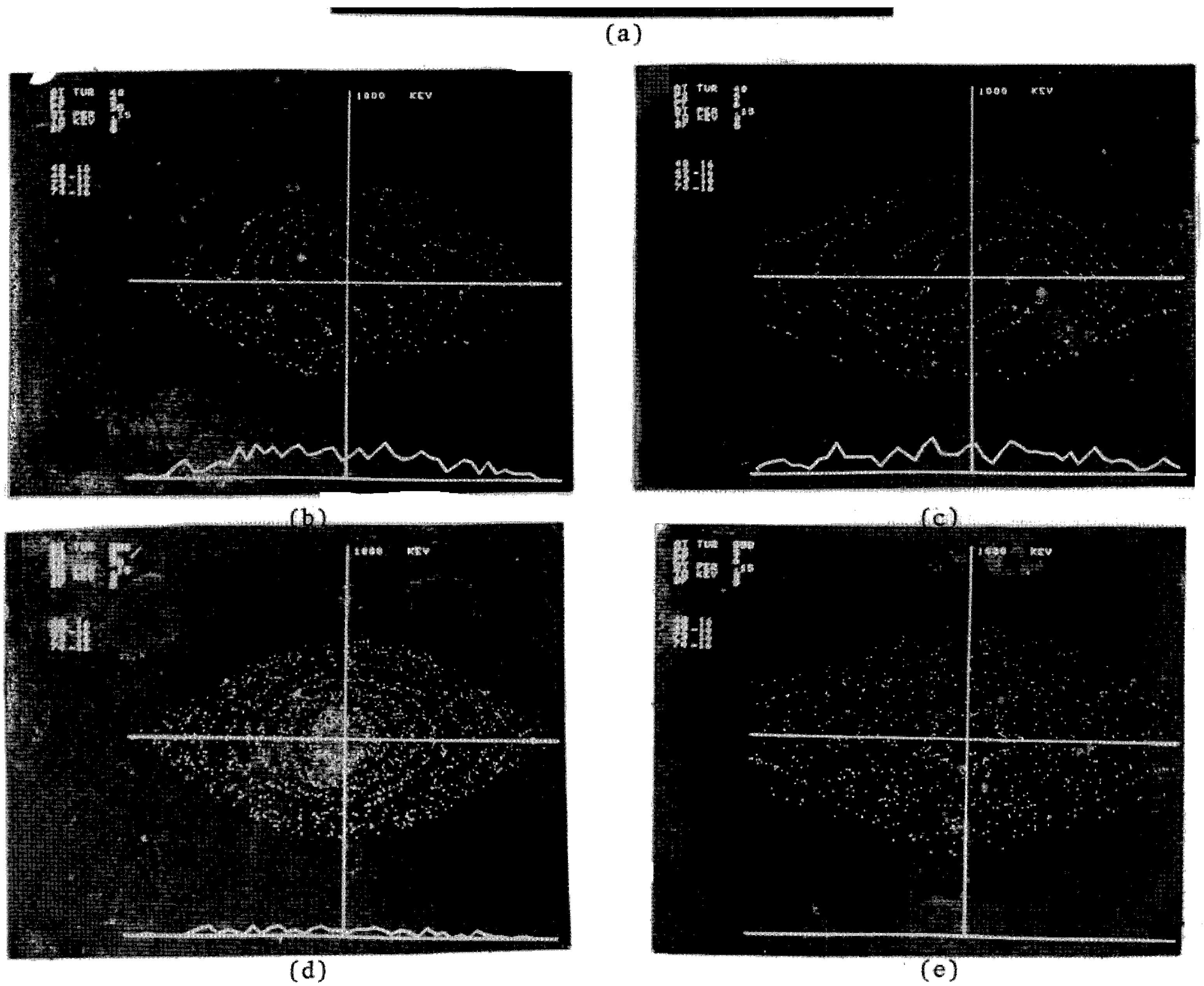


(c)

Figure 3 a) One-hundred particles with energy spread 0.01%
b) After 10 turns
c) After 30 turns



<u>Figure 4</u>

a) Four-hundred particles with energy spread 0.15 % and Linac bunching factor of 5.
b,c) After 40 and 100 turns, slow turn-on
d,e) After 40 and 100 turns, fast turn-on