STATUS OF THE CEA BYPASS FOR COLLIDING BEAMS

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At the 6th International Conference on High Energy Accelerators in Cambridge in 1967, papers were presented by Hofmann, Little, Mieras, Paterson, Robinson, Voss, and Winick, which described how we intend to use the Cambridge Electron Accelerator to store counter-rotating electron and positron beams and do colliding beam work up to energies of 3.5 GeV in each beam. Beams of postrons will be accumulated in multicycle injection mode and beam collisions are to take place in a special bypass, characterized by small value of beta (amplitude function) at the interacton region, resulting in luminosities of the order of $10^{31} cm^{-2} s^{-1}$ with relatively small currents of 100 mA in each beam.

As we had originally envisioned, this colliding beam work is carried out without impairing the usefulness of the accelerator as a synchrotron and in parallel to normal synchrotron operation. All bypass components were installed during normal shut-down periods, all bypass testing so far has been scheduled on a day basis like any other high energy experiment, with only the usual small change-over time involved. Bypass testing has averaged four 8-hour shifts per week during the last year.

This situation will change toward the end of this year when the last component of this colliding beam project—the positron linac—is put into operation. We will then begin to study beam-beam interactions in the bypass, and colliding beam work will take a considerably larger share of the accelerator time.

Beam storage in our synchrotron without use of the bypass was achieved in 1966, after a damping system was installed which redistributes damping rates between betatron and phase oscillations. During the last year the synchrotron vacuum was greatly improved with the installation of ceramic vacuum chambers, thorough cleaning of straight section tanks and pumps and bakeout facilities for the whole ring. At the present time an air equivalent average pressure in the low 10^{-8} Torr range is maintained even during regular synchrotron operation. The 1/e decay time for stored 2 GeV beams is about 45 minutes (this corresponds to one hour at 3 GeV). Beams have been stored for times as long as $2^1/_2$ hours. Because currently the synchrotron is let up to air every three weeks for installation of new components and because no extensive bake-out has been made so far, we expect the vacuum eventaully to become much better. The highest energy of stored electrons was 3.5 GeV, at 2 GeV the largest stored electron current was about 30 mA peak (10 mA average). Stored electron beams with peak currents of the order of 10 mA and larger sometimes exhibit instabilities. The threshold for these instabilities seems to be lower when the ion-clearing system is turned on. Up to now no attempt has been made to study these effects in greater detail, or to improve the situation with octupole lenses or feedback systems. Beam instability observations so far were not very consistent. In some cases f. i., it was possible to store 20 mA of peak current in a stable mode, while ions were swept out of the electron beam.

Filling the ring with positrons will be accomplished in a multicyle injection mode. In each cycle, particles, after off-axis injection at 130 MeV, are accelerated to energies of 2.7 GeV and decelerated again. Radiation damping during the cycle reduces particle oscillation amplitudes sufficiently that at the next energy minimum of the synchrotron magnet cycle new injection is possible. Filling to the design current of 100 mA peak should take only about 16 seconds, that is 1000 injection cycles. Positrons are produced in a tungsten converter which is bombarded with 130 MeV electrons. Positrons are then accelerated to 130 MeV and injected clockwise into the synchrotron ring. Electrons will be accelerated (after the converter is moved out of the beam) to an energy of 250 MeV and injected counterclockwise into the ring. Since the positron accelerator is only now undergoing acceptance tests, all multicycle injection studies to date have been made using 130 MeV electrons. This of course is different from positron injection because of the smaller emittance of the electron beam and because of the possible effect of positive ion collection in a stored electron beam. Also, 130 MeV injection is not quite representative for the ultimate electron injection—at 250 MeV.

Multicycle injection tests were made during 1968 (at the beginning of 1969 we had to shut down (the 130 MeV electron injector in order to install the positron accelerator). During those multicycle injector trials with electrons, we found that electron beams stored in the cycling mode had lifetimes up to 160 seconds, ten times as long as we think is necessary for positron injection (the lifetime is, of course, much shorter than that of a stored 2 GeV beam, because of the larger single scattering losses in the cycling mode at the low-energy portion of the cycle).

Accumulation times however, were generally smaller than decay times. The longest accumulation time we observed was 27 seconds, which means that we accumulated 1620 injection pulses (Fig. 1). During that run a current of a few microamperes of electrons was injected each cycle, resulting in a total accumulated current of the order of 4 mA. As we then increased the amount of injected current per cycle the amount of accumlated beam increased, but far less than proportional, and the apparent fill time decreased. Typically 0.1 mA injection per pulse gave 20 mA accuted mulated current (about 200 cycles fill time); 5 mA injection produced 50 mA current (10 cycles fill time) (Fig. 2). These numbers refer to **peak** circulating current. The **average** currents generally are lower by a factor of 3 (depending on the circumferential fill factor of the ring).

Some experimental facts concerning this apparent saturation in multicycle injection have been quite clearly established:

(1) It is the **peak** circulating current which seems to be limited in multicyclet injecion. Changing the filling factor of the ring seems to have litle effect on the peak circulating current or on the filling time but does change the **average** circulating current.

(2) As the circulating current during multicyle injection increases, coherent horizontal betatron oscillations build up. These oscillations can tbe observsd on rf pickup loops which monitor beam displacement at radiofrequencies from a few megacycles to 475 MHz, the accelerating radiofrequency. Since the amplitude of these displacement signals seems not to be a strong function of the frequency at which one observes this displacement, one can infer that bunches oscillate more or less independently. (The harmonic number of the CEA is 360; thus if one third of the ring is filled, there are 120 bunches.)

(3) Octupole fields decrease the amplitude of the coherent oscillations that build up during multicycle injection and at the same time permit an increase in the current which can be accumulated. To have the most beneficial effect, the octupole fields should vary approximately with the second power of the beam energy. In our tests we have had a match at the low energy part of the cycle only. The resulting increase in accumulated current was about 30%.

(4) Turning on the system for ion collection did not seem to affect the multicyle injection performance. Also there was no evidence of any change in betatron frequencies as the circulating electron current built up. This seems to imply that in the cycling magnetic field of the synchrotron, there are no ions; any ions have alerady been swept out of the beam — and in this respect multicycle filling with electrons may be similar to filling with positrons.

From these observations we assume that radial beam instabilities, perhaps not unlike those observed at Frascati and Orsay, decrease the injection efficiency as the circulating electron current increases. A feedback system would in our case be very difficult to build because of the high harmonic number, but octupole fields seem to be of some value. These instabilities might prevent us at the beginning from reaching the full design current of positrons but since these saturation effects are not too serious up to 20 mA, we expect positron accumulation of at least 20% of the design current in the initial stage of our colliding beam work. We expect to get much closer to the electron design current.

After beams have been accumulated by multicycle injection, the ac component of the synchrotron magnet current is turned off and the dc component is adjusted for the desired particle energy. Then our fast switching magnets are turned on to let the stored beam go through the bypass.

The bypass was assembled about a year ago (Fig. 3 and 4). We began testing the bypass with electron beams in the „ac mode": electrons are accelerated to 2 GeV as in normal synchrotron operation, then are switched into the bypass. Since the particle energy is constant only during a small time interval at the top of the cycle and all bypass magnets are dc powered corresponding to 2 GeV particle energy, it is only possible to obtain a few hundred traversals through the bypass. But this mode of operation has the advantage that it can be repeated at a rate of one cycle per second (the repetition frequency is limited by the power supply for the switching magnets). Since the beginning of this year, bypass tests have been made in the „dc mode", where particles are stored at constant 2 GeV energy before they are switched into the bypass. In this mode, one test cycle (which involves filling the ring, turning off the ac, adjusting the dc energy of the synchrotron magnet, injecting the beam into the bypass, and resetting all the controls for refilling) takes about 3 minutes.

Getting stored beams to go through the bypass with its low-beta interaction region was more difficult than had been anticipated. The very small aperture which the system of synchrotron plus bypass has (about 2.5 cm wide, 1 cm high) makes tolerances very tight. So it is necessary to adjust the particle energy in the synchrotron to within $\pm$·02% before the particles are switched into the bypass. The accuracy of magnet settings in the bypass must be of similar magnitude, to avoid excessive orbit distortions and betatron oscillations and in order to match the phase space emittance of the synchrotron to the synchrotron acceptance. The path length through the bypass has to be correct within a fraction of a centimeter to avoid excessive coherent phase oscillation.

Although it is not difficult to maintain such narrow tolerances, making the initial adjustments is difficult. In particular the electron-optical properties of the synchrotron fringe field through which particles are ejected into the bypass and injected back into the synchrotron were not known to sufficient accuracy to allow us to set up the system by dead reckoning. For this reason we prepared a teletype computer program which calculates betatron frequencies and values for the amplitude function in the synchrotron and in the bypass for given transfer matrices of the synchrotron fringe field and lens strengths of the quadrupole lenses in the bypass. By measuring betatron frequencies and values for the amplitude function in the bypass and in the synchrotron, we were able to improve the input to the computer program and get a better description of the properties of the bypass.

Figure 5 shows a typical picture of pick-up loop signals obtained when the beam is switched into the bypass. The first trace shows the current in the bypass. The second trace shows the signal in a synchrotron current monitor in the non-bypassed portion of the ring. As one can see, the switching into the bypass and back into the synchrotron can be done without any loss of current. The third trace shows coherent vertical betatron oscillations. The fourth trace shows the horizontal displacement in the synchrotron. Coherent betatron and phase oscillations can be seen. Betatron oscillations were excited here by a deliberately wrong steering back into the synchrotron. This gives a convenient and accurate way of determining the betatron frequency. By measuring the change in betatron frequency when the strength of quadrupole lenses in the bypass is slightly changed one can determine the value of the beta function at that particular lens. The coherent synchrotron oscillation is due to a small error in pathlength of the bypass, which causes particles to arrive back in the ring at a slightly wrong phase angle. It turns out that such coherent phase oscillation makes it possible to check the momentumvector match of a beam traversing the bypass by comparing the amplitude of coherent phase oscillation at several pick-up stations.

Through measurements of betatron frequencies and amplitude functions and matching them with the output of our computer, it became possible to improve the lifetime steadily. Decay times of 25 seconds have been observed. At this moment the lifetime seems to be limited by a horizontal aperture smaller then the design value, and an increase in beamwidth. The increase in width may have several causes. Among them are: mismatch of horizontal phase space ellipses or momentum vectors,wrong conditions of the damping system when the beams are switched into the bypass and possibly the effect of non-linear fields causing resonances. (There are indications that for different trajectories through the bypass the beam behaves differently, and that this behavior can be changed by small changes in the betatron frequencies of the beam. Large increases in beam width and height can be observed which do not seem to be current dependent.) These effects need further study. Figure 6 shows the beam cross section in the synchrotron before and about 30 seconds after the beam is switched into the bypass. The real vertical beam size is probably much smaller than indicated by this picture because of the limited resolution provided by the optical synchrotron radiation. The beam size in the interaction region has not yet been measured directly. We have prepared an experimental apparatus for sweeping a 1-micron-thick quartz fiber through the beam with known velocity in a time short compared to the damping time of betatron oscillations. The beam density distribution will be measured by observing the emitted bremsstrahlung. The best computer match to the measured values of the beta function at various places in the synchrotron and in the bypass gives a value for beta at the interaction point of 4″ in the horizontal plane and 7″ in the vertical plane. As soon as we have decreased beam size and increased the apertures, we will try to further decrease beta at the interaction point.

In summary, I would say that the techniques necessary for this project—long-term beam storage in a synchrotron, multicycle filling in a strong focusing synchrotron, and operation of a bypass with a low β section —have been tried out, and that we are hopeful that by the end of this year the study of beam interactions will begin.

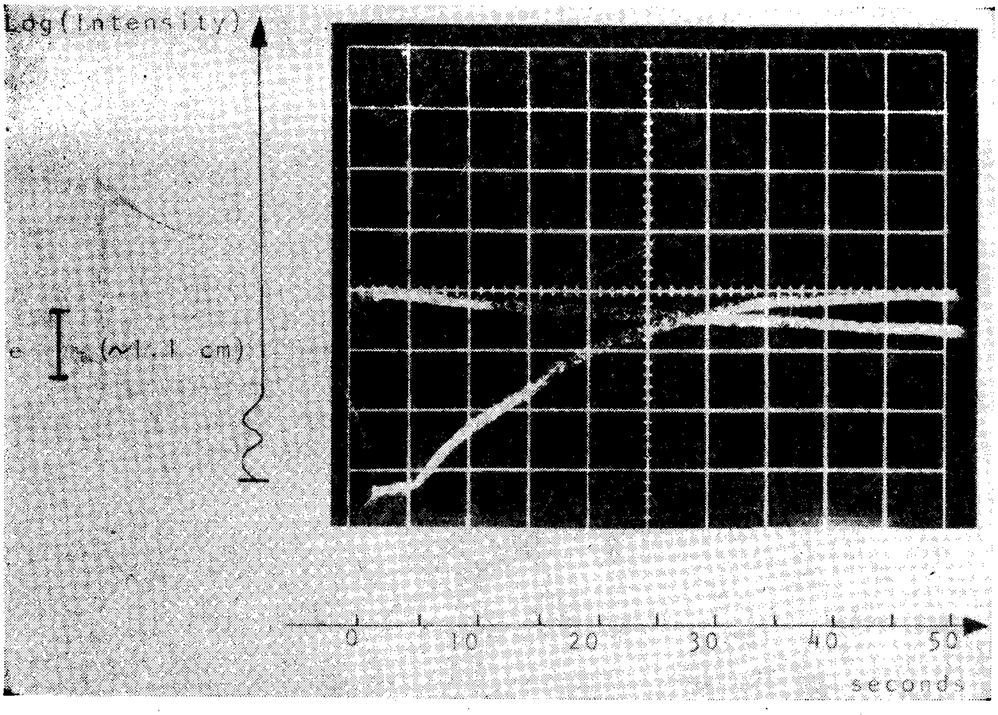

Fig. 1. Multicycle filling and decay. Accumulated current 4 mA

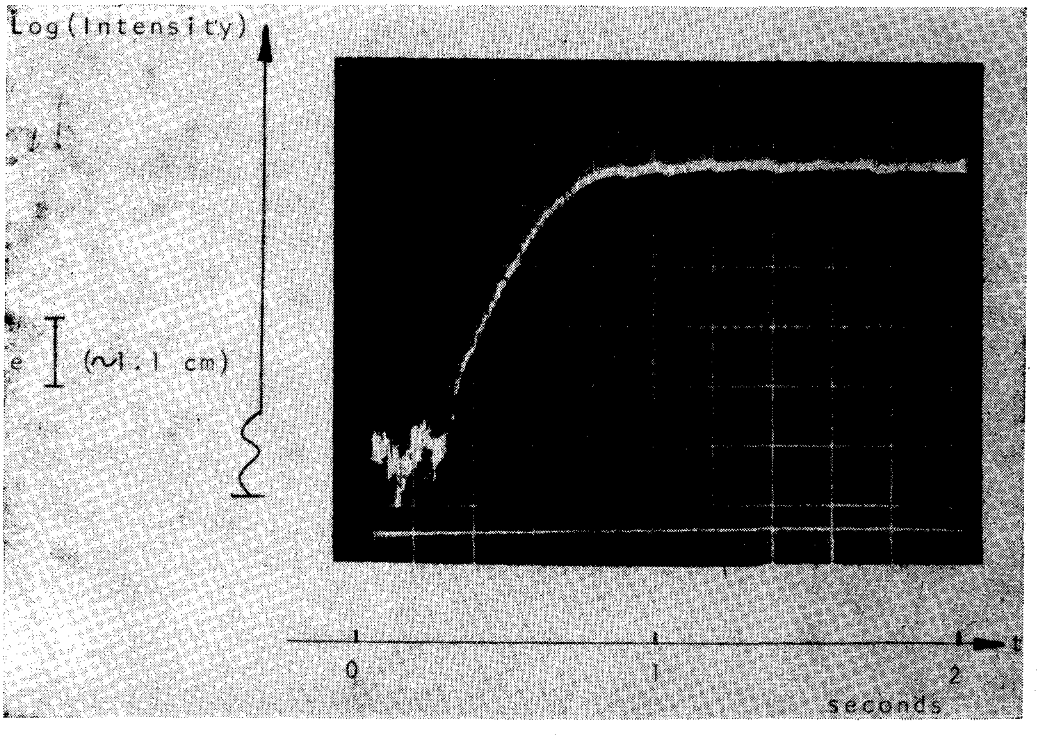

Fig. 2. Multicycle filling. Accumulated current 50 mA

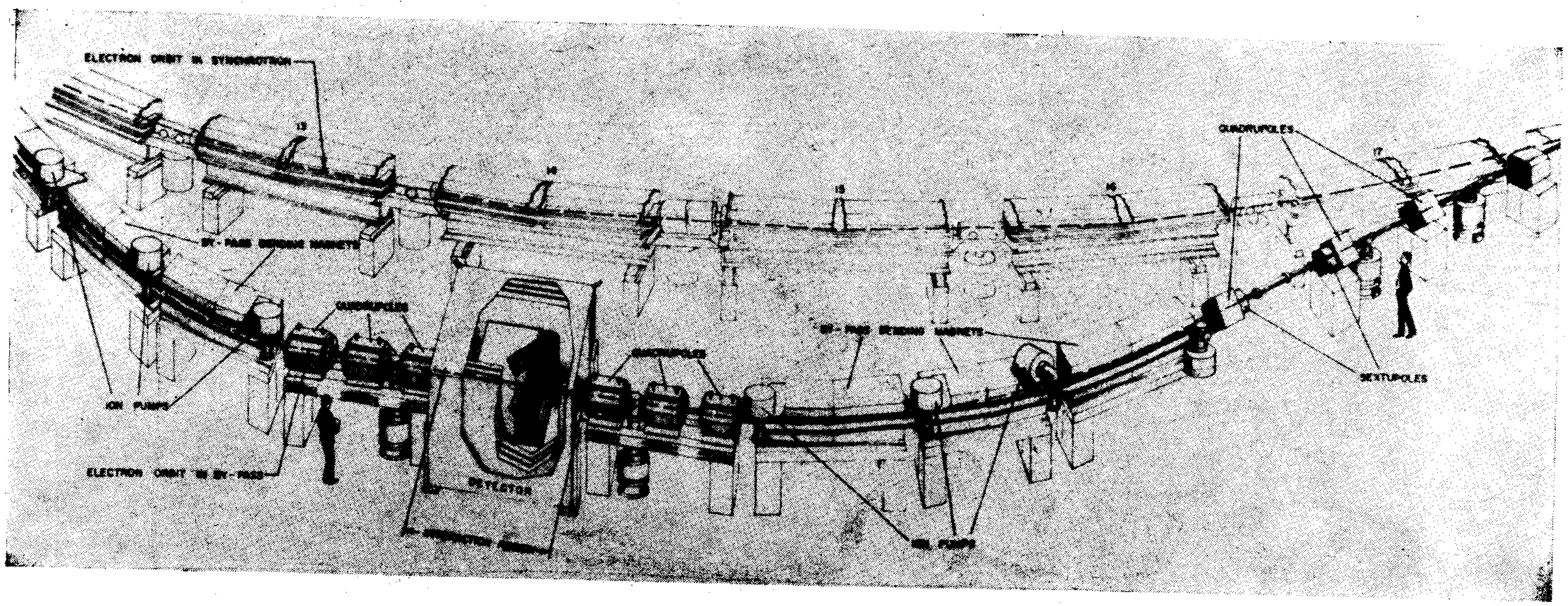

Fig. 3. The bypass sketch

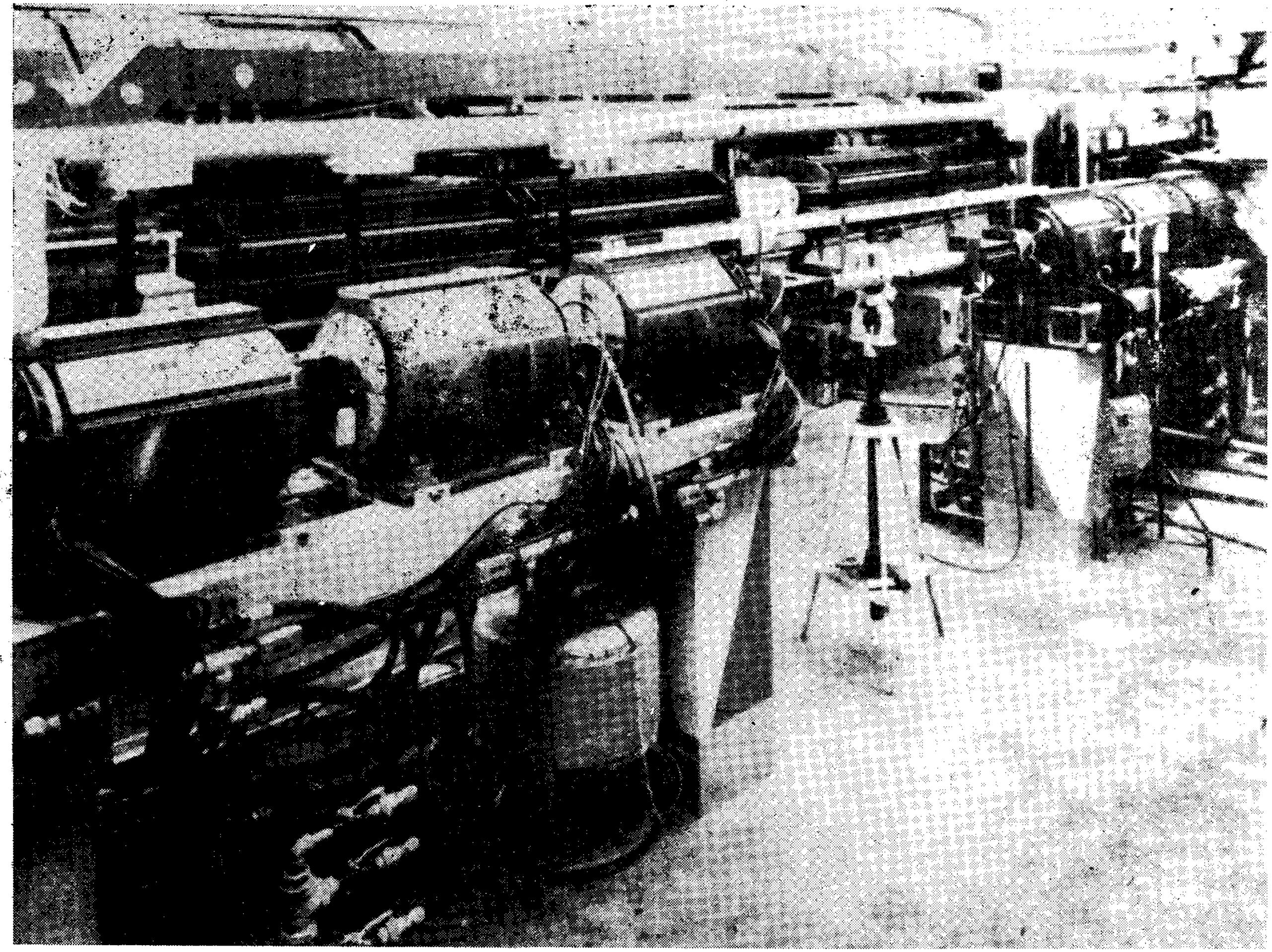

Fig. 4. The photograph of the assemble.

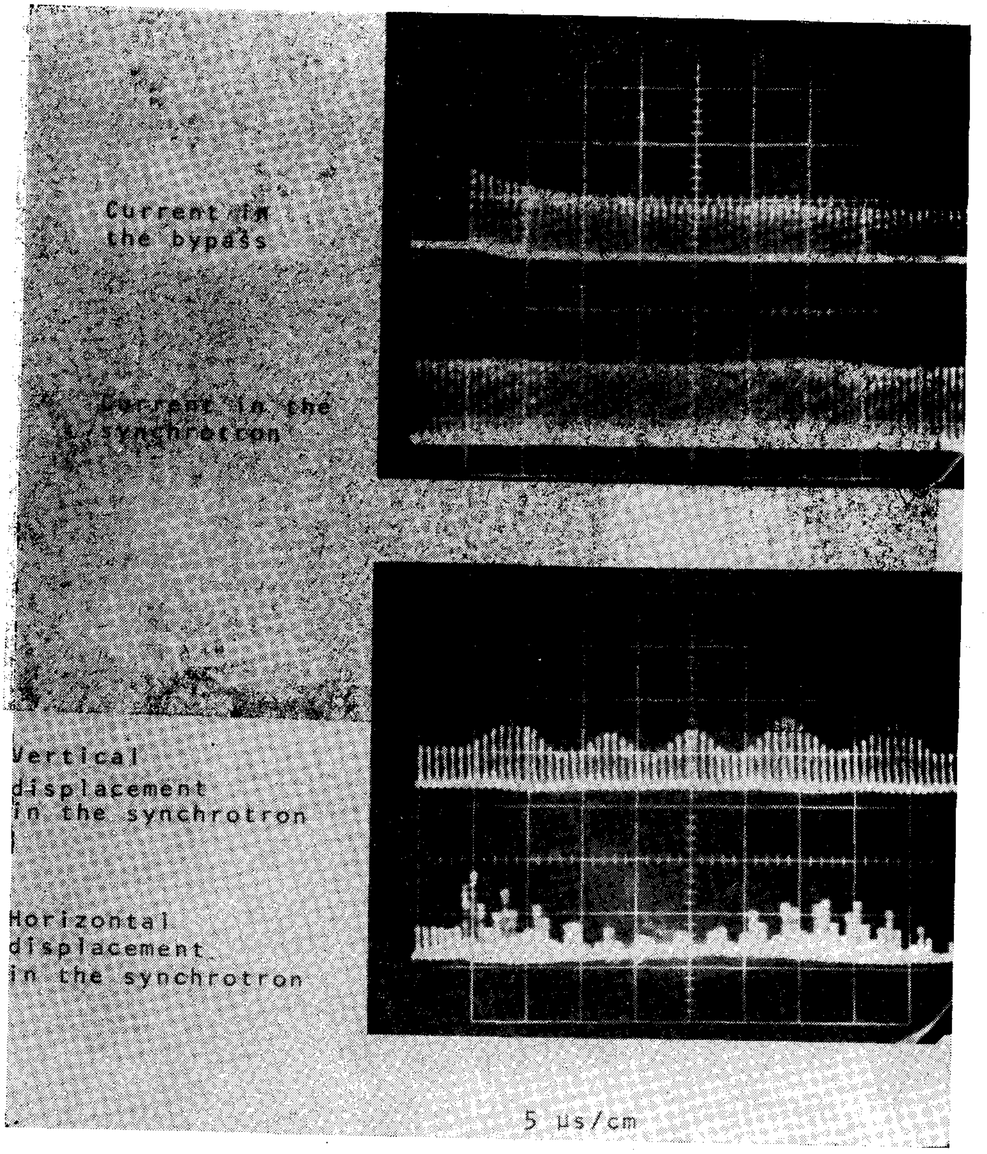

Fig. 5. A typical picture of pick-up signals

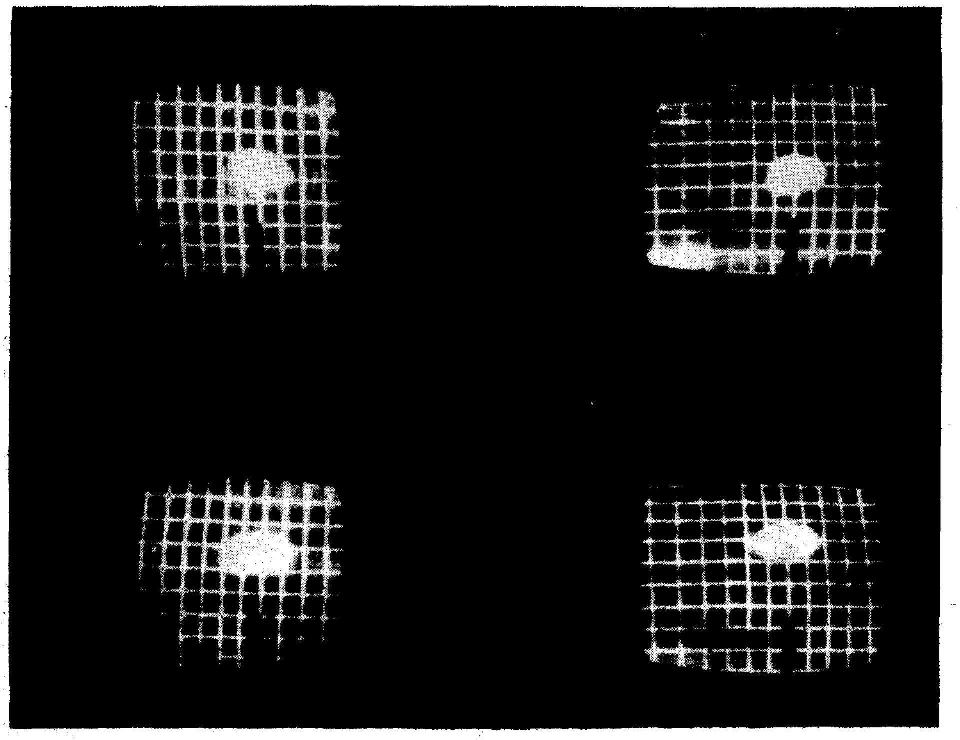

Fig. 6. Beam cross section in the synchrotron. Top: before switching into bypass, bottom: after switching into bypass. Grid: 1 mm squares

ДИСКУССИЯ

Wiedemann: Which is maximum β-function in the first quandrupoles following the intera tion point and which are the alignment tolerances for the quadrupoles? Did you have any difficulties in beam guiding due to maximum closed orbit distortions at the points of the maximum β-function?

Voss: The most critical lense is the center lense of each of the quadrupole triplets. There the vertical beta is about 250 m. Lenses are aligned to within •.1 mm, but the tolerances are much larger, since we steer the beam on its first turn through the by-pass through the centers of all lenses. Since we then put the beam back in the synchrotron on its old equilibrium orbit, this first turn trajectory through the by-pass becomes an equilibrium orbit.

Placidi: Which are the radial and verical β-values near the interaction region?

Voss: At present we have $\beta_r=10$ cm and $\beta_v=17$ cm. We hope to get numbers of $\beta_r=5$ cm and $\beta_v=5$ cm.

Беловинцев: Наблюдаются ли потери электронов при переходе от режима накопления к режиму с постоянным полем?

Voss: If the peak current is smaller than 20 mA, transition from the ac-cycling made to the dc-storage mode is done without current loss. At larger beam currents we sometimes observe beam losses due to instabilities.