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INITIAL MEASUREMENTS OF BEAM BREAKUP INSTABILITY* IN THE ADVANCED TEST ACCELERATOR

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Introduction

This paper reports the measurements of beam breakup (BBU)[1] instability performed on the Advanced Test Accelerator (ATA) up to the end of February 1984. The main objective was to produce a high current usable electron beam at the ATA output. A well-known instability is BBU which arises from the accelerator cavity modes interacting with the electron beam. The dominant mode is TM_{130} at a frequency of approximately 785 MHz. It couples most strongly to the beam motion and has been observed to grow in the Experimental Test Accelerator (ETA),[2] which has only eight accelerator cavities. ATA has one hundred and seventy cavities and therefore the growth of BBU is expected to be more severe. In this paper, BBU measurements are reported for ATA with beam currents of 4 to 7 kA. Analysis showed that the growth of the instability with propagation distance was as expected for the lower currents. However, the high current data showed an apparent higher growth rate than expected. An explanation for this anomaly is given in terms of a "corkscrew" excitation. The injector BBU noise level for a field emission brush cathode was found to be an order of magnitude lower than for a cold plasma discharge cathode. These injector rf amplitudes agree very well with values obtained using the method of differenced $\dot{B}_\theta$ loops.[3]

Experiment

A. Accelerator

The ATA and its initial performance have been described in detail previously.[4,5] In brief, it is a high current induction accelerator designed to produce electron beams of 10 kA peak current at 50 MeV energy and of 70 ns pulse duration. The 85 m accelerator is capable of operating at an average repetition rate of 5 Hz or accelerating ten pulses at 1 kHz. Presently, it consists of a 2.5 MeV injector and 170 accelerator cells, each providing 250 kV acceleration. Power supplies and power conditioning equipment are housed in a building area above the beam tunnel. The output of each pulse power unit is delivered to an accelerator cell through two flexible, oil-filled cables. The power conditioning systems are described in more detail elsewhere.[6]

B. Technique

The method employed to measure rf signals with $\dot{B}_\theta$ loops has been previously described.[7] The growth of the instability with propagation distance through the accelerator is given by the asymptotic formula[1]

$$x \approx x_0 \exp\,(N I \Omega Z_\perp / k_c I_a)$$

where x is the displacement at cavity number N, x_0 is the initial amplitude of the instability, Ω is the angular frequency of the mode, $Z_\perp$ is the product of $Z_\perp/Q$ and Q, I_a is the Alfvén current ($\sim$17,000 $\beta\gamma$ kA) and k_c is the cyclotron wave number $eB/\beta\gamma\, mc^2$. If the amplitude of the BBU is plotted vs cavity number on semilog axes, the slope should permit an experimental determination of $Z_\perp$ if the beam current and tune (B) are known. Extrapolation of the plot back to the injector (cell 10) gives a measure of the BBU noise amplitude generated in the injector.

A second method to determine the injector rf amplitude uses differenced $\dot{B}_\theta$ loops.[3] This is the Mirnov technique where two opposing and differenced magnetic pickup loops produce a signal proportional to the beam displacement provided the current is constant. Two orthogonal sets of opposing loops were placed at the injector output for this measurement.

The technique used to gather the data reported here involved the display of the probe signals on 1 GHz bandwidth oscilloscopes (Tektronix 7104 with 7A29 amplifier and 7B10 time base units). Return wall current monitors ("beam bugs") adjacent to the $\dot{B}_\theta$ loops provided information on pulse-to-pulse variation regarding beam current and position. A second technique consists of using a spectrum analyzer to scan the frequency spectrum on a multipulse basis. This method consumes more time and was only used occasionally.

$\dot{B}_\theta$ loop probes were generally located along the ATA beamline at intercell pump box stations. Each pump box has four diagnostic ports located at the top, east, bottom, and west where the probes were insertable. In practice, only the top and east ports were assigned to $\dot{B}_\theta$ probes. The remaining ports were taken up by vacuum hardware such as pumps, gauges, and by other diagnostics. The output stations of the injector (cell 10) and the entire accelerator (cell 180) held four probes each, in order to gather detailed information at these important locations.

The large number of probe signal channels motivated the installation of four signal highways which could be switched to view a set of four probes simultaneously. Various combinations were possible, such as top probes at four locations, top and east probes at two locations, or all four probes at either injector or accelerator output observations.

Observations

An example of the $\dot{B}_\theta$ loop signals, attenuated 100 x, is shown in Fig. 1 for the case of 7 kA. Traces for beam current, beam charge, and centroid displacements are shown in Figs. 2 to 6. A field emission brush cathode was used for these two cases. The BBU instability grew so rapidly that by cell 100, the oscillations had reached an amplitude of 0.3 cm and by cell 120 the tail end of the pulse had eroded away. As the beam was transported through the rest of the accelerator, more charge was lost in this manner until by cell 180, half of the beam had been lost (Figs. 3,6). The centroid displacements show that the tail had oscillated with large enough

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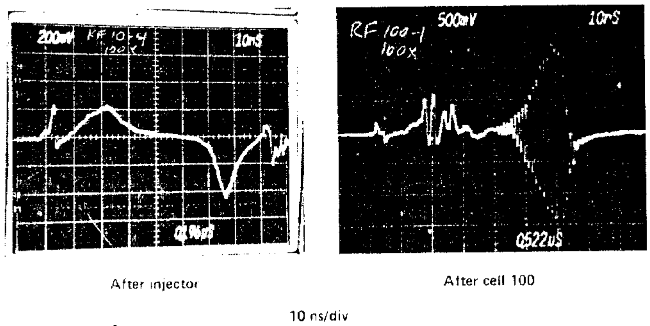

Fig. 1. $\dot{B}_\theta$ loop signals showing growth of beam breakup oscillations for a 7 kA tune.

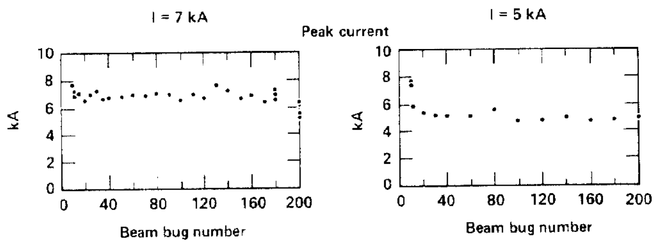

Fig. 2. Beam transport for 7 kA vs 5 kA, slow risetime with brush cathode - peak current comparison.

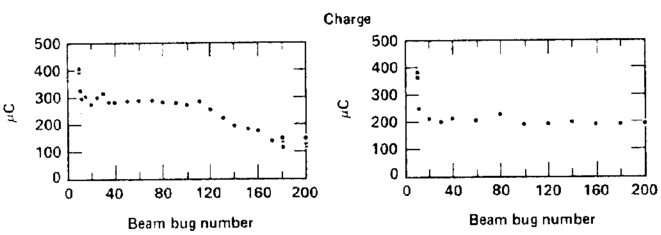

Fig. 3. Charge transport comparison for 7 kA vs 5 kA.

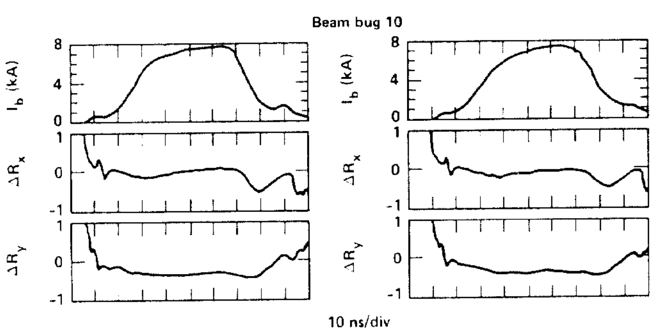

Fig. 4. Current traces showing slow risetime and small centroid displacements at injector output.

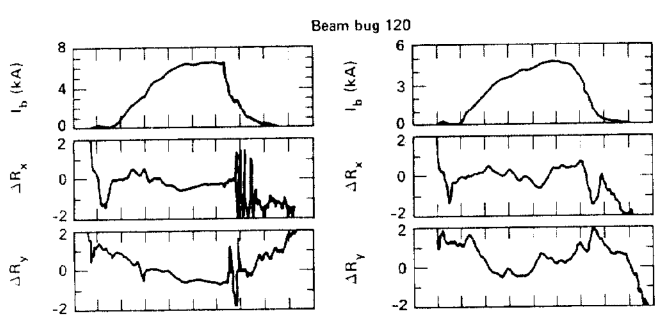

Fig. 5. Beam breakup oscillations eroding tail of beam for 7 kA case.

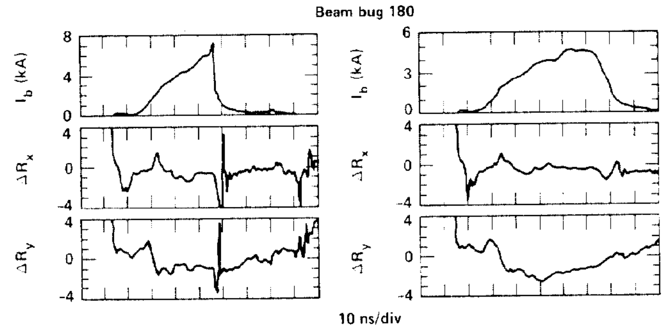

Fig. 6. Transport of full beam for 5 kA case as compared to tail erosion for 7 kA case.

amplitude to be lost at the pipe wall (6.75 cm). A second 7 kA case that had a faster risetime was also studied. It showed tail erosion occurring even earlier. Thus, less total charge was transported to the accelerator output.

A 5 kA case is compared to the 7 kA case, both having a slow risetime. Some initial loss of peak current and pulse length occurred between the injector and the first cell block. From cell 20 onwards, practically all the charge in the 5 kA case was transported through to cell 180. Note that at the output the maximum centroid displacements were much smaller than in the 7 kA case.

The peak amplitudes of the BBU oscillations were measured at various cell positions of ATA. Figure 7 shows plots of peak amplitudes vs cell numbers. The cathode for the 7 kA plot was a field emission brush cathode, whereas the 5 kA plot was for a cold plasma discharge cathode. The plots show that $Z_\perp$ for the 5 kA case was measured at 35 ± 5 Ω, whereas the 7 kA value was 52 ± 5 Ω. A 4 kA case (not shown here) also gave a value close to the 5 kA case. The injector BBU oscillation amplitude was 4×10^{-4} cm for the field emission cathode, while the amplitude for the discharge cathode was an order of magnitude higher.

Analysis and Discussion

The measured value of $Z_\perp$ for the 4 and 5 kA case is very close to the predicted value of 28 - 32 Ω, based on ETA measurements of $Z_\perp/Q$ and Q.[5] The ATA cavities are nearly identical to the ETA cavities, although more mode dampening ferrite has been added to the ATA cavities resulting in lower Q's. The $Z_\perp/Q$ is somewhat affected by the presence of the dampening ferrite so that values determined from the ETA experiments must be corrected for the lower Q's of the ATA cavities. The cavity mode model[8] shows that the $Z_\perp/Q$ will rise slightly as the Q of the mode is reduced. In the case of ATA, reducing the cavity mode Q down to approximately 4 results in an increase of some 11% in the value of $Z_\perp/Q$ over the ETA values. Thus, the expected range of $Z_\perp/Q$ for ATA is 7 to 8 Ω at a Q of 4.

The method of differenced $\dot{B}$ loops gave an injector noise amplitude of 1.3×10^{-4} cm for the brush cathode and a value ten times higher for the discharge cathode. These compare well with the present values.

The data for 7 kA show an anomalously high growth rate which can be qualitatively explained by a purely kinematical effect called the "corkscrew" mode.[9] If one considers the propagation of an initial transversely displaced beam pulse with a head

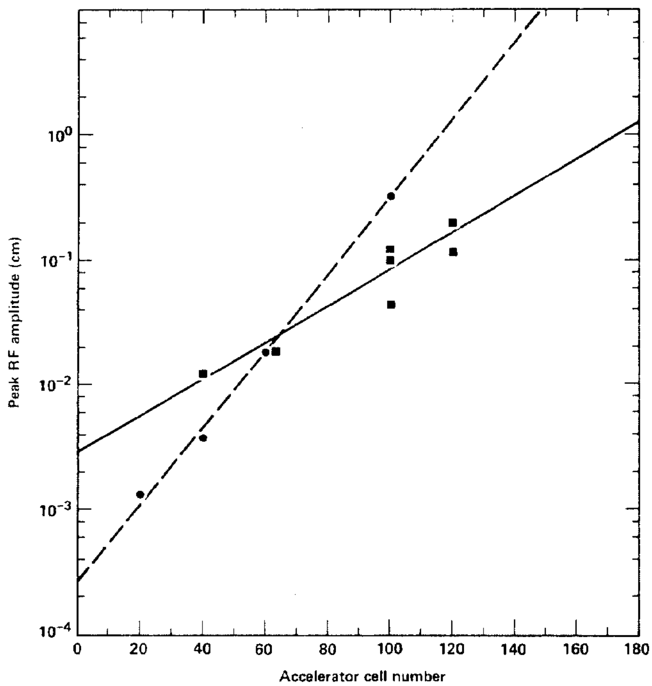

Fig. 7. Growth of BBU in 7 kA case (dotted line) is anomalously higher than in 5 kA case (solid line). Injector rf amplitude (cell 10) is ten times higher for brush cathode than for discharge cathode.

to tail variation of energy through a solenoidal transport region one finds that the frequency content of the transverse displacement shifts toward high frequencies as the beam propagates. This effect occurs because beam slices with slightly different energies will have slightly different cyclotron frequencies. After a large number of cyclotron orbits, the slices can be up to 180° out of phase with each other. This will occur when $k_c z\Delta\gamma/\gamma \approx \pi$. For a sinusoidal variation of γ with time through the pulse with frequency ω_0 the amplitude of the nth harmonic of ω_0 is $2x_0 J_n(k_c z\Delta\gamma/\gamma)$ where x_0 is the initial transverse displacement of the beam and J_n is the usual Bessel function of order n. Thus, even a relatively low frequency energy modulation has a frequency component at the BBU frequency which will eventually attain amplitude $2x_0$. In ATA this offset was typically a few mm.

The source of the energy variation in ATA is the nearly critically damped circuit response of the accelerator cavity-pulse power drive system.[9] The beam current is an excitation source for this circuit which has a resonant frequency of ≈50 MHz. The magnitude of the energy variation is proportional to the peak beam current and can approach 20% near the head of the beam pulse. Thus $\Delta\gamma$ increases with beam current and the 16th harmonic (≈800 MHz) grows more rapidly in axial position. If the increase in this harmonic due to the corkscrew is more rapid than the normal BBU growth, then the BBU growth will appear anomalously high at higher beam currents.

Techniques that may reduce the BBU instability level include (a) minimizing the injector noise, (b) a slower risetime, (c) a faster ramp-up of B_z near the injector, (d) a low pressure IFR in the accelerator (spoiled vacuum) and (e) laser guiding. Of these approaches, laser guiding has been found to be effective and is currently employed at ATA.

Conclusions

The growth of the BBU instability for low currents on ATA is about as expected on the basis of theory and previous experience with ETA operation. The "corkscrew" excitation mechanism can qualitatively account for the anomalously high growth rate of BBU for the higher current. The injector noise level was ten times lower for the field emission brush cathode than the cold plasma discharge cathode. The obtained values agree very well with direct measurements of the injector rf amplitudes using the method of differenced $\dot{B}_\theta$ loops.

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