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PROPAGATION STUDIES WITH CHOPPED ELECTRON BEAMS*

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PROPAGATION STUDIES WITH CHOPPED ELECTRON BEAMS

ABSTRACT

An experimental study of chopped electron-beam propagation is described in this report. Earlier studies of hose instability suppression by modulation ("partial chopping") of the beam current had given encouraging results. In the present studies, a technique for achieving fully chopped beams was developed, and experiments on propagation over distances up to 18 m were carried out. The experimental evidence indicates significant stabilization, in spite of the rather strong transverse perturbations that are introduced by the chopping procedure.

FACILITY AND MAJOR DIAGNOSTICS

The basic facility for these tests is shown in Fig. 1. The equipment, which is the same as described in Refs. 1 and 2 except for the chopper and kicker, consists of the following:

1. The Astron induction linear electron accelerator. This accelerator produces a beam current up to 600 A with a kinetic energy of about 5 MeV, a pulse length of 250 ns, and a beam quality of about 0.02 rad-cm.
2. The 120-MHz energy modulator and magnetic buncher ring.
3. The 18-m-long, 1.2-m-radius gas chamber.
4. The paddle chopper. This is a narrow paddle that can be adjusted to a radial position in the buncher ring such that it intercepts the particles with energy near the average while passing most of the high and low energy particles. With careful tuning of magnets and adjustment of the paddle, a bunched beam can be produced with zero current between peaks (and with only a 10 or 20% decrease of peak current). The 60-MHz transverse-deflection chopper was tried and discarded. It caused excessive transverse deflections of the bunched beam pulses.
5. The kicker. The first 50 ns or so of the accelerator pulse is always relatively "noisy." The kicker is a transverse deflector excited by a charged line that was built for Astron tests. It can be adjusted so that the transverse force is on for the first 50 ns of the beam pulse, deflecting the beam off of an aperture. After this time, the deflecting force decays rapidly to zero and the beam current passes through the aperture to the gas chamber. Use of the kicker usually improved beam propagation. The present kicker causes a detectable beam deflection for about 50 ns after the nominal turnoff time of the force.

Fig. 1. Plan view of accelerator, energy modulator, magnetic buncher ring, and gas chamber.

The most important measurements are made using the following instruments:

- Resistive wall shunts. These are mainly in the vacuum beam transport upstream of the gas entry film. They measure the beam current as a function of time, $I_b(t)$. They can also give the axial and azimuthal time-dependent position of the center of mass of the beam, with a minimum time resolution of about 50 ns.³

- Rogowski belts. These are relatively large diameter current detectors in the gas chamber. They are usually used in pairs – one measuring the sum of beam current and plasma current, $I_b(t) + I_p(t)$, and an identical belt a few centimeters downstream measuring the primary beam current only, $I_b(t)$. The downstream belt is in a vacuum chamber, and the primary beam passes through a thin film which excludes the plasma current. The difference of the two signals is $I_p(t)$.

- 70-GHz interferometers. These measure $\int n_e d\ell$ along a path perpendicular to the plasma channel, where n_e is the plasma electron density.

- X-ray-producing-wire/phototube-detector combinations for plotting the radial profile of the primary beam current density (corrected by an Abel integral inversion under the assumption of axial symmetry).⁴

- Faraday cups for measuring the primary beam current passing through a small hole. Figure 2 shows the basic features of these instruments. The current collected on the inner conductor of an open-ended coaxial transmission line is measured. The transmission line is terminated with a resistance equal to the characteristic impedance at the oscilloscope. The hole has a diameter of 1/4 inch or less and so passes only a small fraction of the beam. This protects the instrument in two ways: (1) The heat per pulse deposited in the inner conductor is limited and so the temperature of the inner conductor is limited (the inner conductor cools mainly by radiation to the water-cooled outer conductor). (2) The voltage across the cable and cable connectors is limited. The Faraday cup has always been used to measure the primary beam current only; it is in a separate vacuum chamber and is shielded from plasma current by a thin foil. Errors in the measured current due to secondary electron or thermionic electron currents appear to be less than 10%. This was determined by noting that the signal is unchanged when fixed positive or negative bias voltages large compared to the signal voltage are applied to the inner conductor using a blocking capacitor between the instrument and the oscilloscope. This Faraday cup (essentially a point detector) has been useful for several measurements:

1. It appears to have accurate nanosecond time resolution and so can measure the time-dependent current density in the bunched and chopped beam.

2. In the case of a continuous beam, i.e., the case where I_b is independent of time, time-dependent signals can often be related to transverse motion of the center of mass of the beam relative to the detector or to axially symmetric changes in beam current density.

3. It can be moved transversely across the beam and thus (using many pulses of the accelerator) plot the radial current density profile. This is the same information

Coaxial transmission line characteristic impedance,
 $Z_0 = 60\sqrt{\mu/\epsilon} \ln r_o/r_i = 60\sqrt{1} \ln 2.3 = 50$ ohms

Fig. 2. Schematic diagram of Faraday cup.

as obtained from the x-ray-wire technique, but with the Faraday cup there is the advantage that the Abel integral inversion and the assumption of axial symmetry are unnecessary.

4. TV cameras for observing the channel light and the entry film light.

OBSERVATIONS WITH 2-METER PROPAGATION PATH

This section presents measurements using a Faraday cup located a relatively short distance from the gas entry film ($z = 2$ m). The instrument is mounted on a radial support and can be remotely positioned at continuous points along a diameter of the gas chamber.

Transverse Hose Oscillations of Continuous Beam and Relative Stability of Bunched Beam

Figure 3 shows the signal produced by transverse oscillations of the continuous beam and the reduction in amplitude which occurs when the energy modulator is switched onto the beam. The top oscillogram is a measurement of the continuous beam current as a function of time. The time-integrated Rogowski belt that produced the signal is not shielded from plasma current, but the plasma current is negligible through the last 2/3 of the beam time. The beam current is about 170 A. The third, fourth, and fifth oscillograms show the time-dependent Faraday current for three transverse positions of the detector relative to the time-averaged position of the center of mass of the beam. Each picture is an overlay of about four successive pulses, and there is seen to be a large amount of reproducibility in the signals. This means that the signal is due to an amplification of a reproducible perturbation originating in the accelerator, and not a random perturbation. There is a phase difference of π radians between the signals seen by the detector on opposite sides of the peak beam density. Also, the centered case has twice the frequency of the noncentered cases (in the centered case the peak beam density passes over the detector whereas in the noncentered cases it does not). Since these two observations are predicted for transverse beam oscillations, we conclude that the beam is oscillating transversely. The period of oscillation τ is about 40 ns. The second picture from the top shows the signal from a Faraday cup located at $z = 0.3$ m. There is seen to be a large increase in oscillation amplitude between $z = 0.3$ and $z = 2$ m.

The observed increase in amplitude is not inconsistent with the predictions of simple theory. For a $\sin(\omega t)$ transverse perturbation at $z = 0$, the predicted maximum "steady-state" hose amplification is

$$A = \exp(0.35 k_{\beta} z), \quad (1)$$

where k_{β} is the wave number for the incoherent betatron oscillations of individual beam particles due to the attractive self-force. For uniform current density inside a circular beam envelope of radius a ,

Fig. 3. Continuous-beam transverse oscillations and the stabilizing effect of beam current modulation (0.5 Torr N_2 , overlays of many pulses).

$$(k_{\beta}a)^2 = 2 \frac{(I/c)(f - 1/\gamma^2)}{\beta\gamma(m_0c^2/e)\beta^2}, \quad (2)$$

where I/c is the current in emu, $m_0c^2/e = 1705$ emu, $\beta = v/c$, $\gamma = (1 - \beta^2)^{-1/2}$, and f is the fractional neutralization of the electrostatic field. We will set $f = 1$. For 170 A and $\gamma = 11$, Eq. (2) gives $k_{\beta}a = 0.0425$. The Faraday cup measures the current which passes through a small hole. For these measurements the Faraday hole radius was $a_F = 0.318$ cm. For the fourth picture of Fig. 2, the time-averaged Faraday current is $I_F = (700 \text{ V}/50 \Omega) = 14$ A, so the beam radius is

$$a = a_F \sqrt{\frac{I}{I_F}} = 0.318 \sqrt{\frac{170}{14}} = 1.1 \text{ cm},$$

and

$$k_{\beta} = \frac{0.0425}{1.1} = 0.039 \text{ cm}^{-1}.$$

For $z = 200$ cm, $k_{\beta}z = 7.8$. Substituting this value into Eq. (1), we find that the predicted maximum hose amplification is $A = 15$.

In the last picture, modulator off is compared with modulator on. Switching on the modulator reduces the oscillation to an undetectable amplitude. Switching on the modulator causes the beam entering the gas to be bunched and it also reduces the time-averaged beam current density by about a factor of two; both effects are predicted to have a stabilizing influence. k_{β} is proportional to $\sqrt{J}$ where J is the beam current density. If we multiply the value of k_{β} calculated above by $1/\sqrt{2}$ and substitute into Eq. (1), we predict a smaller amplification, $A = 6.9$, for the bunched beam behaving as a continuous beam of the average current. Switching on the modulator is observed to decrease the amplitude by a larger factor than $15/6.9$, and this is evidence that bunching stabilizes, or at least reduces the growth rate of, the long-wavelength hose.

Measurements of Relative Amplitude of Continuous-Beam Hose Oscillations at Several Gas Pressures (Plasma Conductivities)

In Fig. 4 the continuous beam oscillations are compared for several different N_2 gas pressures. For each case the signals are compared with the detector located on opposite sides of the time-averaged position of the peak current density. The phase difference of π radians shows that the oscillation is transverse. For each pressure the signals were recorded with three different values of the maximum frequency passed by the oscilloscope system. There are seen to be two frequencies present, one with the 40-ns period of Fig. 3 and the other having about an 8-ns period. The amplification is seen to depend on pressure (i.e., conductivity) — the amplitude of the 8-ns oscillation increases by about a factor of 4, and the amplitude of the 40-ns oscillation decreases slightly, as the pressure is increased from 0.2 to 5 Torr.

Fig. 4. Continuous-beam transverse oscillations at different N_2 gas pressures (200 A, 2-m Faraday cup with 1/4-in.-diam hole, overlays of many pulses).

In Fig. 5 the theoretical growth rate in the variable $k_\beta z$ is plotted vs $\omega\tau_d$ for the "steady state" solution for a $\sin(\omega t)$ transverse perturbation at $z = 0$. The measured relative amplitudes at $z = 200$ cm are fitted to the curve making use of the more general version of Eq. (1),

$$A = \exp\left(\frac{I_m k}{k_\beta} k_\beta z\right), \quad (3)$$

and using $k_\beta z = 8$. (We assume that the theory worked out for a single perturbation frequency holds for each frequency separately.) There is also the constraint that at each pressure $\omega\tau_d$ for the 8-ns oscillation is five times that for the 40-ns oscillation. With the self-consistent fit of the points on the curve, we can read off $\omega\tau_d$ for each pressure and calculate τ_d knowing the frequency.

τ_d deduced from Fig. 5 is plotted vs N_2 gas pressure in Fig. 6. τ_d decreases from about 4 ns at 0.5 Torr to 1 ns at 2 Torr and then becomes independent of pressure for higher pressures. For uniform conductivity inside a cylindrical channel of radius R ,

$$\tau_d = \frac{4\pi\sigma R^2}{c^2(2.4)^2}, \quad (4)$$

and the low-frequency, nonreactive conductivity is given by

$$\sigma = \frac{e^2 n_e}{m_0 \nu_m}, \quad (5)$$

where n_e is the plasma electron density and ν_m is the momentum-transfer collision frequency. The neutral gas molecule density is much larger than the ion density and so ν_m is proportional to the gas pressure. At high pressures n_e is proportional to pressure (production by binary collisions between beam particles and gas molecules and negligible recombination), and so τ_d is independent of pressure. At pressures from 2 Torr down to 0.02 Torr there is an anomalously large n_e , apparently produced by streaming instability.

Credence is added to this model for the pressure dependence of τ_d by the two lower curves in Fig. 6. The 70-GHz interferometer located at $z = 0.15$ m measures $\int n_e dl$ along a diameter of the gas chamber (which is proportional to n_e at constant channel radius). So the interferometer reading divided by gas pressure would be proportional to conductivity (or τ_d). This curve has a shape similar to that for τ_d in that it becomes independent of pressure at high pressure and increases at low pressure. The monopole plasma current is measured with a Rogowski belt after the turnoff of the primary beam current. The corresponding decay time constant is also plotted in Fig. 6. τ_m is proportional to σ , and this curve has a pressure dependence similar to that of the other two measurements.

Fig. 5. Theoretical steady-state hose instability growth rate in $k_\beta z$ vs $\omega \tau_d$ for $\sin(\omega \tau)$ transverse perturbation at $z = 0$, and self-consistent fit of measured amplitudes, for two frequencies and five N_2 pressures.

Fig. 6. Dipole decay time constant from Fig. 5, interferometer reading divided by gas pressure, and monopole decay time constant, all vs N_2 pressure.

Momentum-Dependent Perturbation of the Bunched Beam

A serious shortcoming has been found in the modulator-buncher system. The position and direction of the center of mass of the beam at $z = 0$ is not completely independent of linear momentum, as it would be in an ideal system. This is shown in Fig. 7, where the horizontal position of the beam is measured at $z = 2$ m for small variations in the linear momentum. The plots of beam current density vs transverse position were made by moving the detector continuously and using many pulses of the accelerator. The signal is sampled during a 3-ns interval located 20 ns earlier than the time of trace-brightening on the left-hand traces. The momentum was varied by deactivating a few cores of the accelerator (8 kV/core). The beam moved transversely 3 cm, or through an angle

$$\theta = \frac{3}{200} = 0.015 \text{ rad,}$$

for a fractional change of energy of

$$\frac{\Delta E}{E} = \frac{4 \times 8}{5000} = 0.006 .$$

The buncher system produces pulses of current which have high energy at the head and low energy at the tail. For 120 MHz the pulses are sharp peaks about 2 ns wide at half-maximum height, and the amplitude of the fractional variation of energy is about ± 0.03 . Based on the above calibration we would predict that the tail would be deflected 0.15 rad relative to the head. Figure 8 shows plots of the time-integrated 2-m Faraday signal for the bunched beam vs transverse position at several pressures of H_2 gas. At the lowest pressures there is a single peak about 4 cm wide at half-maximum height. As the pressure is increased the curve becomes wider, and at 20 Torr there appear to be two partially resolved peaks about 10 cm apart. At the lowest pressures τ_d is long compared to the pulse width and so the tail is predicted to oscillate in the field left by the head. At high pressure τ_d is shorter. If τ_d is small compared to the time between head and tail, then the tail would lose the dipole plasma current memory of the head and "go its own way." (The magnetic self-focusing of the individual sections would still be present.) Presumably the two peaks which are seen at small τ_d are about 1 ns apart in time, and the earlier peak has higher energy. Figure 9 shows the bunched beam signal with nanosecond time resolution at low pressure (long τ_d) and high pressure (shorter τ_d). At short τ_d , very narrow pulses are seen as the beam sweeps across the detector.

The apparent angle between head and tail of the pulses measured at 20 Torr H_2 in Fig. 8 is about 0.05 rad. This is a large perturbation by any standard; e.g., it is comparable to the maximum transverse angle in the incoherent motion of the individual particles in the equilibrium beam. It is remarkable that the bunching stabilization works as well as it does with this large initial interpulse distortion.

Fig. 7. Transverse profiles of continuous-beam current density using 2-m Faraday cup, showing the effect of small variations of linear momentum (200 A, 0.5 Torr N_2).

Fig. 8. Transverse profiles of beam current density modulated at 120 MHz using 2-m Faraday cup, comparing different H_2 gas pressures (200 A).

Fig. 9. Beam current density vs time compared for two H_2 pressures (120-MHz modulation, 2-m Faraday cup, nanosecond time resolution).

PROPAGATION OF BUNCHED AND CHOPPED BEAM TO 18 METERS

This section presents the different measurements made on optimized propagation through the full length of the gas chamber. For this set of measurements:

1. The beam current in the accelerator was limited to about 300 A so that the amplitude of accelerator instability would not be excessive.
2. The time-averaged beam current in the gas chamber was about 110 A. The loss of beam current between the accelerator and the gas chamber was due to loss at the beam kicker aperture plate, loss in the paddle chopping, and loss at the collimator at the entrance to the gas chamber.
3. The accelerating voltage was carefully adjusted as a function of time through the accelerator pulse to produce a relatively constant momentum (fractional variation about 10^{-3}). Otherwise the beam is perturbed by sweeping transversely near $z = 0$ with a characteristic time of 50 to 200 ns.
4. The buncher magnets were carefully tuned and the paddle chopper was carefully adjusted to produce uniform high peaks of beam current with zero current between peaks.
5. A relatively low gas pressure of 0.2 Torr Ar + 0.2 Torr H₂ was used. This results in a relatively long τ_d which limits the tendency for the tails of the pulses to separate from the heads. It also limits the growth of the hose oscillation within a single short pulse. If τ_d is increased until it is long compared to the 8-ns pulse period, then the beam could develop a long-wavelength hose oscillation similar to a continuous beam with the same average current.

Figure 10 is a horizontal section view of the gas chamber showing the location of the principal diagnostics. Figure 11 shows two TV views of the time-integrated light from the channel. In the upper picture the beam enters at the upper right, and the view is from a mirror at $z = 3$ m at the side. The lower picture is through a mirror located at $z = 16$ m in the bottom looking upstream, and the beam enters the picture at the bottom. Under these optimized conditions, the TV views show a channel with a uniform diameter of about 10 cm and no evidence of instability.

Figure 12 shows the time-averaged beam current passing through large-diameter detectors at several z -positions. The time-averaged beam current is about 110 A at $z = 1$ m. At 18 m the head of the beam is lost; following the head the current increases and is about 85 A at the end of the accelerator pulse.

Figure 13 shows signals from the Faraday detectors. The upper three pictures show the bunched and chopped current vs time at three sweep rates at $z = 2$ m. The bottom two pictures compare the time-averaged current density at $z = 2$ m and 18 m. At 18 m the head of the beam is lost (as was also seen with the 18-m Rogowski belt). The conductivity produced by the bunched beam is known to increase with time in the accelerator pulse, and presumably the improved propagation at the tail of the accelerator pulse is associated with the higher conductivity. The maximum current density at 18 m is about half that at 2 m. Scattering is predicted to decrease the equilibrium current density at 18 m to 0.76 of its value at 2 m, so this process accounts

Fig. 10. Plan view of gas chamber showing location of instruments.

Fig. 11. TV view of channel light.
Top: Looking downstream through
a side mirror at $z = 3$ m. Bottom:
Looking upstream through a bottom
mirror at $z = 16$ m.

Fig. 12. Total current vs time at different axial positions.

50 NS/DIV

20 NS/DIV

10 NS/DIV

2 m FARADAY
1 GHz BANDWIDTH

50 NS/DIV

2 m FARADAY
1/4 IN. DIAM. HOLE
20 V/DIV
20 MHz
OVERLAY

50 NS/DIV

18 m FARADAY
1/4 IN. DIAM HOLE
8 V/DIV.
20 MHz
OVERLAY

Fig. 13. Modulated beam current density vs time, measured with Faraday cups at 2 m and 18 m.

for part of the observed decrease of current density. Using the model of the previous section with an average beam current of 100 A and a beam radius of 3 cm, we calculate $k_\beta = 1/92 \text{ cm}^{-1}$. At $z = 18 \times 10^2 \text{ cm}$ the maximum hose amplification is $\exp(0.35 k_\beta z) = 950$. This amplification of continuous beam hose is obviously not occurring, presumably because of the stabilizing effect of the beam bunching.

Figure 14 shows signals from a single-turn B_θ magnetic induction pickup loop located at $z = 0.3 \text{ m}$ and 2 cm from the gas chamber axis. For the upper picture the time resolution is short enough so that the 120-MHz signal is measured; for the lower picture the 120-MHz signal is averaged out and only the signals from the head and tail of the primary accelerator pulse are seen. The amplitude of the 120-MHz signal is reduced by induced plasma current which may be characterized by a monopole decay time constant, τ_m , which increases with time during the accelerator pulse so that the amplitude $\tilde{v}$ of the 120-MHz loop voltage decreases by about a factor of 3 from head to tail. τ_m may be reduced from the measurements

$$\tilde{v} = K \left. \frac{\partial I}{\partial t} \right|_{\text{max}} = K \omega \tilde{I}, \quad (6)$$

where $\tilde{I}$ is the amplitude of the 120-MHz total current and K is a constant which is proportional to the loop area and to r^{-1} , where r is the radial distance of the loop from the beam axis. Simple theory predicts

$$\frac{\tilde{I}}{\tilde{I}_b} = \frac{1}{\sqrt{1 + (\omega \tau_m)^2}}, \quad (7)$$

where $\tilde{I}_b$ is the amplitude of the 120-MHz beam current. The constant K may be eliminated by noting that the time integral of the voltage from the head or tail of the beam (from the lower picture) is proportional to the average beam current, $(I_b)_{\text{av}}$:

$$\int V_{\text{av}} dt = K(I_b)_{\text{av}}. \quad (8)$$

Also, Faraday cup measurements show that

$$\tilde{I}_b \approx (I_b)_{\text{av}}. \quad (9)$$

Combining Eqs. (6) through (9) gives

$$\frac{\tilde{v}/\omega}{\int V_{\text{av}} dt} = \frac{1}{\sqrt{1 + (\omega \tau_m)^2}}. \quad (10)$$

Fig. 14. Induced voltage vs time on small B_{θ} loop at $z = 0.3$ m, 2 cm off axis.

Near the tail of the accelerator pulse $\tilde{V} \approx 0.5$ volt (from the upper picture). From the lower picture $\int V_{av} dt \approx 15 \times 10^{-9}$ V-s (at the head of the pulse). Substituting these values and $\omega = 2\pi \times 120 \times 10^6 \text{ s}^{-1}$ into Eq. (10) gives $\tau_m \approx 30$ ns near the tail of the pulse.

Figure 15 gives measurements of beam-current-density radial profiles at 2 m using the Faraday detector, and at 13 m using the x-ray-producing wire technique. Late in the accelerator pulse the diameter is about 6 cm at half-maximum height at both locations. Early in the pulse at 2 m the curve is wider, again confirming the picture that the tails of the 2-ns pulses tend to separate from the heads at low conductivity (early time).

Figure 16 shows the signals from the 70-GHz interferometer located at $z = 0.15$ m. The maximum phase shift is about $3\pi/2$ and the corresponding $\int n_e d\ell$ is $3.9 \times 10^{13} \text{ cm}^{-2}$. The ionization takes hundreds of nanoseconds to decay.

Figure 17 shows the signals from the accelerator-pulse momentum analyzer. On the upper trace one large division corresponds to $\Delta p_z/p_z \approx 0.002$.

DISCUSSION

During the testing period reported on here the equipment was considerably improved and extended. In particular, tests showed that the 60-MHz transverse deflection chopper perturbed the beam excessively (even when passive), and it was discarded. The paddle chopper was substituted and it seems to work quite well. Its performance can probably be improved by installing more beam position monitoring and steering on the buncher. The Faraday cups which measure current density and can be used with nanosecond time resolution have been particularly useful.

Transverse hose oscillations of the continuous beam were detected with the Faraday cup at 2 m, and the dependence of the amplification on tickling frequency and gas pressure (conductivity) was used to deduce the time constant for dipole plasma current decay. Switching on the 120-MHz energy modulator (bunching) stabilizes the oscillations. The stabilization is probably due to the beam bunching. There is the complication that the average current density is lower with the modulator on than off, and this decreases the growth rate of the continuous-beam hose oscillation. It does not appear that this effect alone can explain the stabilization.

We found that the buncher is not as ideal as might be desired in that elements of beam with different momenta follow measurably different paths as they enter the gas chamber. This was found to be the main origin of the slow (50-to-200-ns-period) transverse beam sweeping. After careful minimization of time-dependent momentum variation through the accelerator pulse, the amplitude of slow sweep was notably reduced.

The ~2-ns beam bunches have relatively high momentum at the head and low momentum at the tail, and this together with the deficiency of the buncher mentioned above has the result that the tail is deflected ~0.05 rad relative to the head. If τ_d is long compared to the bunch length, the tail oscillates transversely in the field left by

Fig. 15. Current density profiles at two axial positions.

Fig. 16. Signals from the 70-GHz interferometer.

Fig. 17. Signals from the momentum analyzer.

the head; if τ_d is short compared to the bunch length, the tail separates from the head. This model fits all of the experimental observations. The amplitude of the perturbation can be reduced by increasing the modulation frequency, since the amplitude of energy modulation required for optimum bunching varies as $1/\omega$.

Measurements were made on a bunched and chopped beam (120 MHz) with about 100 A time-averaged current and 3 cm radius propagating to 18 m. The channel conductivity is observed to increase throughout the accelerator pulse. At 18 m the beam density is almost zero at the head of the accelerator pulse and increases throughout the pulse. At the tail the density is ~ 0.5 times that at 2 m.

REFERENCES

1. ARPA Beam Research Program, Lawrence Livermore Laboratory Rept. UCRL-51566 (May 13, 1974) (title U, report SNSI).
2. J. W. Beal, R. J. Briggs, and L. D. Pearlstein, Beam Research Program, Recent Results and Status, Lawrence Livermore Laboratory (Dec. 1972).
3. T. J. Fessenden, B. W. Stallard, and G. G. Berg, Rev. Sci. Instrum. **43**, 1789 (1972).
4. J. M. Leary, E. J. Lauer, and V. W. Shuler, Determination of Radial Beam Profile by Measuring X-Ray Intensity vs Position of a Wire Target, Lawrence Livermore Laboratory Rept. UCID-16598 (Sept. 24, 1974).

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