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BUNCHED BEAM NEUTRALIZATION*

G. M. Gammel, A. W. Maschke, and R. M. Mobley†

Summary

One of the steps involved in producing an intense ion beam from conventional accelerators for Heavy Ion Fusion (HIF) is beam bunching. To maintain space charge neutralized transport, neutralization must occur more quickly as the beam bunches. It has been demonstrated at BNL that a 60 mA proton beam from a 750 kV Cockcroft-Walton can be neutralized within a microsecond.[1] The special problem in HIF is that the neutralization must occur in a time scale of nanoseconds. To study neutralization on a faster time scale, a 40 mA, 450 kV proton beam was bunched at 16 MHz. A biased Faraday cup sampled the bunched beam at the position where maximum bunching was nominally expected, about 2.5 meters from the buncher. Part of the drift region, about 1.8 meters, was occupied by a series of Gabor lenses. In addition to enhancing beam transport by transverse focussing, the background cloud of electrons in the lenses provided an extra degree of neutralization. With no lens, the best bunch factor was at least 20. Bunch factor is defined here as the ratio of the distance between bunches to the FWHM bunch length. With the lens, it was hoped that the increased plasma frequency would decrease the neutralization time and cause an increase in the bunch factor. In fact, with the lens, the instantaneous current increased about three times, but the bunch factor dropped to about 10. Even with the lens, the FWHM of the bunches at the position of maximum bunching was still comparable to or less than the oscillation period of the surrounding electron plasma. Thus, the electron density in the lens must increase before neutralization could be effective in this case, or bunching should be done at a lower frequency.

I. Experimental Set-Up

The apparatus is shown in Figure 1. A duoplasmatron source in the Cockcroft-Walton is used to produce a 100 mA, 450 keV proton beam. The beam passes through a removeable 10% mesh followed by a 40 kV, 16 MHz buncher and the drift region. A Faraday cup with a 2.2 cm aperture sampled the beam at the end of this region. The Gabor lenses are shown. It was found that the grounded inner rings were needed to initiate lens action. Operating characteristics of the lens are given in Table I. The Faraday cup was a shielded 1/16 inch thick Al plate with a 70% transport screen mesh about 1/2 cm in front of it which could be biased to ± 300V. The cup aperture was a few inches from the end of the Gabor electrode. With the 10% mesh out, the typical current collected through the aperture with 1 kV on the lens but no lens magnet, and no bunching, was 1 mA.

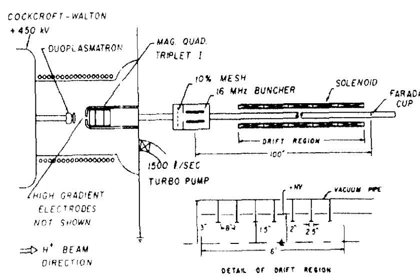

Figure 1. Experimental apparatus

II. Experimental Results

The first step was to measure the bunch factor with the lens off. The oscilloscope used for measurements of bunch width had a total bandwidth of 400 MHz. Figure 3.a. shows typical oscilloscope traces. A summary of the basic results appears in Table I.

For comparison with theory, Table I includes results from a 1-D computer program, written by A. W. Maschke for 10,000 particles divided into 500 bins, and from a 1-D analytical model. The former included a random energy spread, but ignored space charge. A 1000 eV energy spread gave results corresponding to the experiment. However, the expected spread was more like 100 eV (characteristic arc temperature), for which the bunch factor is 80. Results from a corollary program including space charge showed that the actual factor should begin to decrease when the Faraday cup current exceeds 5 mA. As will be seen later, this was the case when the lens was on, and the bunch factor did decrease 2 or 3 times.

The analytical model, which is actually a combination of two models, takes space charge into account. One of the models, accurate as long as the bunch length greatly exceeds its radius, was analyzed by Khoe.[2] In this model, the space charge debunching force increases monotonically until bunching can no longer continue. For a 20 kV buncher, Khoe's formula predicts a bunch factor of 45 at 20 mA. It was found that the minimum bunch length was less than its radius, so the second model, a 1-D pancake model of the bunch, applies. With this model, the space charge debunching force is independent of the bunch length. Thus, a bunch factor larger than 45 would be expected.

Based on these theoretical results, the oscilloscope used would have been bandwidth limited. One device used in an attempt to increase the bandwidth was a 1 GHz crystal. Sample outputs appear in Figure 3.b. The diode in the crystal had to be reversed, and this modification derated the bandwidth such that its response to the bunched signal was down a factor of 3 or 4 from the response to the DC signal. According to the data in Figure 3.b. there was no change in bunch factor between low current and high current cases. This was verified in the lens off case by inserting the 10% mesh and looking at the direct signal from the Faraday cup. The best bunch factor measured was 20. Being bandwidth limited, it could have been at least double this, corresponding to a minimum bunch length of about a centimeter.

The second step was to measure the bunch factor with the lens on, and observe whether or not the bunch factor increased. To be effective, the electron density would have to be increased enough to follow a 3 nanosecond perturbation. Setting this equal to half of a plasma oscillation period yields a critical density of 5×10^8 electrons/cc. One would perfer a density several times larger. Now, the peak current collected by the Faraday cup with the lens on was at least 20 mA. If the ambient electron density was enough to neutralize a DC beam of this current, that gives 0.4×10^8 electrons/cc, so almost all the additional electrons must come from the lens. As given in the paper by R. M. Mobley in these proceedings,[3] the electron density due to the lens, if the lens is working properly, is

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†Brookhaven National Laboratory, Upton, N.Y.

$$\frac{4\epsilon_0}{e}\frac{V}{b^2}$$

V = lens voltage

b = lens radius

Table II shows that the lens was working as expected. For V = 2 kV, this is 2 x 10^8 electrons/cc, which is below that needed for longitudinal neutralization. The lens may create more electrons, the difference being balanced by positive ions which did not have time to diffuse out of the lens. An experimental measure of the density was obtained by measuring the voltage drop at P as shown in Figure 2.

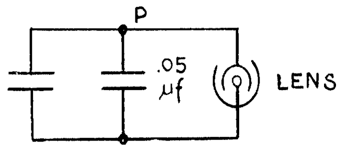


Figure 2. Circuit for measuring electron density in lens. ΔV at P was typically 80V.

From $\Delta Q = C\Delta V$ and from the fact that the ratio of density outside the grounded rings (radius = a) to that inside the lens is $b^2/(b^2 - a^2) \sim 2.4$, the electron density in the lens can be inferred. The result was several times the theoretical value. The lens, then, was probably on the verge of being helpful for longitudinal neutralization. The observed factor of two ratio in bunch length for the lens on to lens off cases is indeed approximately that expected assuming no neutralization. The increase may have been due to the more intense bunches pulling electrons out of the Faraday collector plate before actual impact. This possibility, which has not been ruled out, would mean that the lens is clearly aiding neutralization. The bunch factor returned to 20 when the 10% mesh was inserted with the lens on.

III. Conclusions

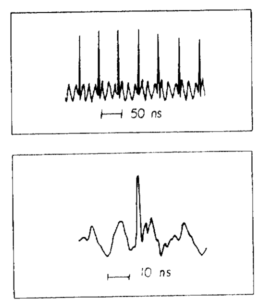
The bunches are certainly expected to be unneutralized with no lens. If the electron density was really that given by theory. It must increase by at least a factor of 10 before the electrons could follow and neutralize 3 nanosecond wide bunches. Alternatively, bunching could be done at a lower frequency. If the electron density was higher, some neutralization may have been expected to occur, but, partly because measurements were at the edge of bandwidth limitations, it was difficult to detect.

TABLE I

Bunch	Experiment lens off	Experiment lens on	Theory (unneut.beam) Computer	Theory (unneut.beam) Analytical
Bunch Factor	20	10	<80	>45
FWHM	3 ns	6 ns	>0.7 ns	<1.5 ns

TABLE II

	Experiment	Theory
Successful operating voltage range	1 kV-2.5 kV	any voltage
Solenoid field strength	~110 Gauss	≥53 Gauss at 1.5 kV
Pressure	≤2 x 10^{-6} torr	-
Maximum current magnification factor	12	11.3 - 13
Length to image at 2 kV	72"	>50", <94"
Focussed spot size	≤2 cm	~1.3 cm
n_e at 1.8 kV	<(12)x10^8 cm^{-3}	1.5x10^8 cm^{-3}



500 mV → for a), 50 mV for b), 100-V for c)

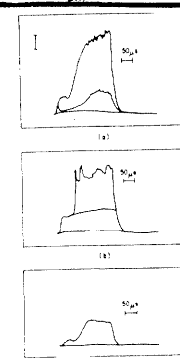


Fig.3a. Sketches of Faraday probe outputs

Fig.3.b. Sketches of crystal detector outputs for in order of increasing amplitude: no lens only; lens and rf. The lens was not used for trace c).

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References

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