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PRECOOLING IN THE ANTIPROTON ACCUMULATOR

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Summary

The result of detailed calculations on the stochastic precooling of the momentum spread is presented. The effect of feedback via the beam is included and found to be small, as already suggested by the ICE experiments.

1. Introduction

In the design report for the antiproton accumulator [1] a preliminary version of the precooling system was described. Since then, further calculations were made, taking into account many details that were disregarded initially.

The original version was found to be too optimistic in two important respects:

a) From recent measurements, it appeared that the sum pick-ups that will be used will have an effective impedance of 12.5 ohms instead of the 50 ohms originally assumed. This is mainly because of the ferrite losses that affect the pick-up response more than was foreseen. The signal-to-noise ratio at the input of the chain will therefore be lower even though twice as many pick-ups as originally planned will be used.

b) It was realized that the precooling system will be somewhat disturbed by the stack cooling system, because the kickers for the latter surround the complete beam including the newly injected pulse. The expected value of this additional heating term ($\frac{1}{2}d\overline{E^2}/dt = 6 \times 10^{11}$ eV^2s^{-1} near the precooling notch) was established in the course of the detailed design work reported in [2].

Fortunately, it appeared possible to offset these effects to a certain extent by a different filter design, based on a better optimizing strategy. It may also be possible to improve the cooling by using a larger bandwidth than originally foreseen.

2. Optimizing method

In the orginal version, the filter was optimized by varying its components in such a way that the r.m.s. gain over the entire passband was as low as possible, while maintaining within the Schottky bands a phase shift less than 30^o

and a gain proportional with frequency to within a 30% tolerence. This minimized the output power due to amplifier noise; the conditions imposed were, however, somewhat arbitrary.

The output power will be limited by practical considerations. There is an optimum gain (corresponding to an optimum power level) that results in the most efficient cooling, but a considerable reduction with respect to this optimum is found to be possible without too much affecting the final result. Low power is interesting not only for reasons of cost, but also because nearly all the power will be dissipated in the ferrite of the kickers mounted in ultra-high vacuum. Moreover, spurious excitation of betatron oscillations due to deflecting field components in the kickers will be reduced if the power is kept low.

A new optimizing routine therefore follows the entire cooling process up to the end and computes the percentage of the injected particles that are collected within the final momentum spread after the given cooling period (2.2 s). This percentage is the quantity that is optimized by variation of the filter parameters and of the system gain vs time, varying stepwise every 0.2 seconds. The gain is limited in such a way that the total output power (due to Schottky noise and amplifier noise) will never exceed a specified value.

With this optimizing criterion, it was found that the best performance is given by filters that exhibit a phase shift at the edge of the distribution that is much higher than the 30^0 originally allowed. A stronger non-linearity of the gain vs frequency was also found to be advantageous.

3. Filter configuration

Many filter types were tried, including the one shown in the design report, ref. 1, fig. 6.3) that contained lumped elements to make the damping dependent on the harmonic number. It finally appeared that the best results are obtained with the simple filter of fig. 1.[4] The use of lumped capacitors or inductors, or series-connected resonant combinations of lines as in [1] or of lines with slightly different length to provide damping just outside the Schottky bands was found to be unprofitable.

Both resonant lines have the same electrical length. Their impedance is given by the expressions in fig. 1.

The loss factor $(\alpha l)_{av}$ was assumed to be 0.002 for the shorted line, 0.05 for the open one. To obtain 0.002, a large-diameter line (eg 0.2 m), together with a compensating circuit as used in the ICE experiments will be required.

The ratios R_1/Z_{L1}, R_2/Z_{L1} and Z_{L2}/Z_{L1} were optimized by the programme.

4. Details of the calculation

An initial rectangular distribution, containing 2.5×10^7 particles within a full $\Delta p/p$ of 1.5% was assumed. The fraction collected into a full-width $\Delta p/p = 0.167\%$ after a cooling period of 2.2s was calculated.

To reduce the amount of calculation, only four harmonics (regularly spaced) were treated; the result was, of course, scaled to the full number of harmonics within the passband.

The calculation of the heating due to amplifier noise assumed amplifiers with a 1.95 dB noise figure. An additional heating due to the stack cooling system, equal to one half the amount mentioned in para. 1, was added; it seems possible to gain at least a factor 2 by feeding part of the stack cooling signal in opposition into the precooling kickers.

Mixing between pick-ups and kickers was taken into account by introducing the appropriate energy and harmonic-dependent phase shifts.

Further assumptions were:

- pick-up impedance 12.5 Ω
- kicker impedance 50 Ω

- number of pick-ups 200
- number of kickers 200
- $\eta = p\Delta f/f\Delta p$ -0.1219

Feedback through the beam, according to the theory given in ref. 3 was taken into account. This effect was estimated by fitting the distribution obtained every 0.2s with the approximation

$$\psi(E) = (C/E^2 + 1/\psi_o)^{-1}$$

where ψ_o is the central density (E = o) and C is determined so as to give the required total number of particles. The complex system gain was then corrected, using the expressions in fig. 21 and equation (48) of ref. 3.

The reduction of output power by the beam feedback is small and was therefore disregarded. The reduction of the interference from the stack system by the feedback was also neglected.

5. Results

Fig. 2 shows the fraction collected versus maximum output power for three different passbands. Obviously, a large bandwidth is advantageous.

Some calculations were made to establish the sensitivity of the result to certain parameters. For this purpose, a nominal power of 1 kw with a passband of 150 - 500 MHz was assumed. The results are shown in Table 1.

Clearly, the filter parameters are far from critical. Nevertheless leaving out R_2 and Z_{L2} completely will reduce the captured fraction by a significant amount.

The number of particles collected varies as shown in fig 3. with the number injected.

TABLE 1

Parameter varied	nominal value	changed to	other parameters reoptimized	change of collected fraction
$(\alpha l)_{av}$ of shorted line	0.002	0.02	yes	-0.038
$(\alpha l)_{av}$ of open line	0.05	0.5	yes	-0.015
heating by stack system	$3 \times 10^{11} eV^2 s^{-1}$	6×10^{11}	yes	-0.009
R_1/Z_{L1}	0.63	0.50	no	-0.002
		0.75	no	-0.001
R_2/Z_{L1}	0.26	0.21	no	-0.002
		0.31	no	-0.001
Z_{L2}/Z_{L1}	0.20	0.25	no	-0.002
		0.30	no	-0.006
amplifier noise figure	1.95dB	3.0dB	yes	-0.036
R_2 and Z_{L2}	removed		yes	-0.049

Fig 4 shows how varying the η value of the lattice could improve the collection efficiency. The optimum occurs at the value where the Schottky bands at the highest frequencies just begin to touch each other. Beyond this point the filter method becomes less efficient. The actual value (0.1219) is, of course, below the optimum. Increasing it would, however, require a lower transition energy; this would result in a lower horizonzal acceptance of the ring.

The feedback via the beam reduces the cooling term of the Fokker-Planck equation that describes the cooling process (co-efficient F) as well as the heating terms (coefficients D_1 for amplifier noise and D_2 for Schottky noise). The reduction factors are plotted vs. $\Delta p/p$ in fig. 5. Despite these large reductions, the finally collected fraction only decreases by 5.3%. This corresponds to the ICE results that appeared to confirm the theory even without taking the feedback effect into account.

Fig. 6 shows the final density profile and the ratio Schottky noise/ amplifier noise, as far as their contribution to the heating terms is concerned. The actual power ratio is 0.95 at the beginning and 0.12 at the end of the cooling period.

Around the working point considered, it appears to be most advantageous to vary the gain slightly during the cooling period so as to keep the total output power constant up to the end, despite the diminution of the Schottky noise as the beam is cooled. This could be done in a simple way by detecting the output power, comparing it with a reference and adjusting the gain with a simple, not too fast feedback system. A total gain increase by a factor of about 1.3 is needed.

Only at higher powers (above 3 kW) a reduction of the gain and the power at the end of the cooling period becomes profitable.

Finally, it should be noted that in all these results, the actual average amplifier power is quoted. To prevent frequent overloading by the noisy character of the signal, the amplifier rating should be higher by at least a factor 3 and a fast recovery after overload is essential.

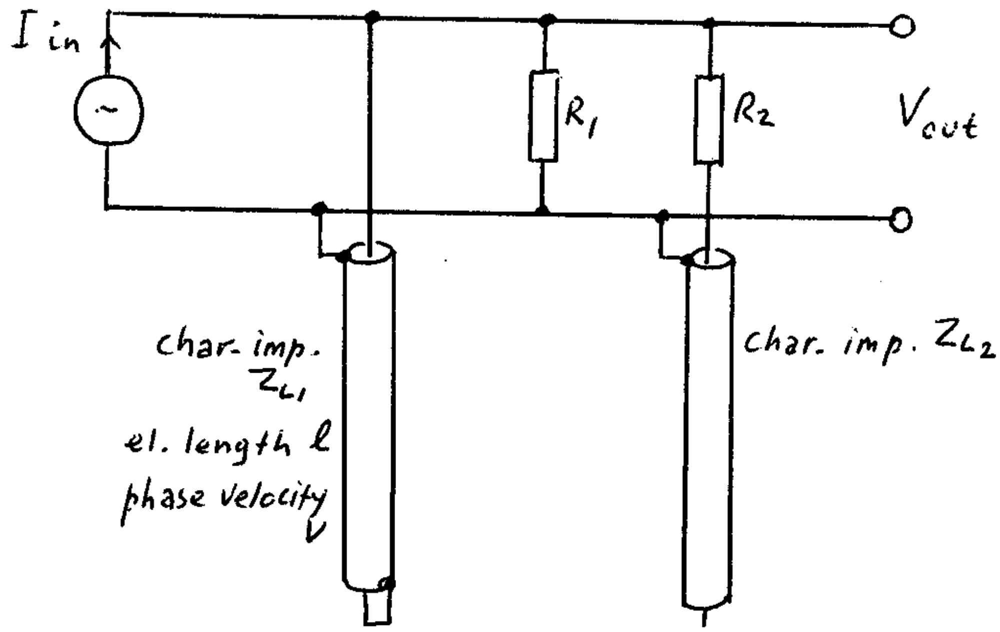
References

1. Design Study of a Proton-Antiproton Colliding Beam Facility, CERN/PS/AA/78-3

2. S. van der Meer, Stochastic Stacking in the Antiproton Accumulator, CERN/PS/AA/78-22

3. F. Sacherer, Stochastic Cooling Theory, CERN/ISR/TH/78-11

4. This filter type was proposed by L. Thorndahl.



impedance	shorted	line	$Z_{L1} \tanh(\alpha_1 + j\beta)\ell$
	open	line	$Z_{L2} \coth(\alpha_2 + j\beta)\ell$

with $\alpha\ell = (\alpha\ell)_{av} \sqrt{f/f_{av}}$

$$\beta\ell = \frac{2\pi\ell f}{v}$$

Fig 1. Filter configuration

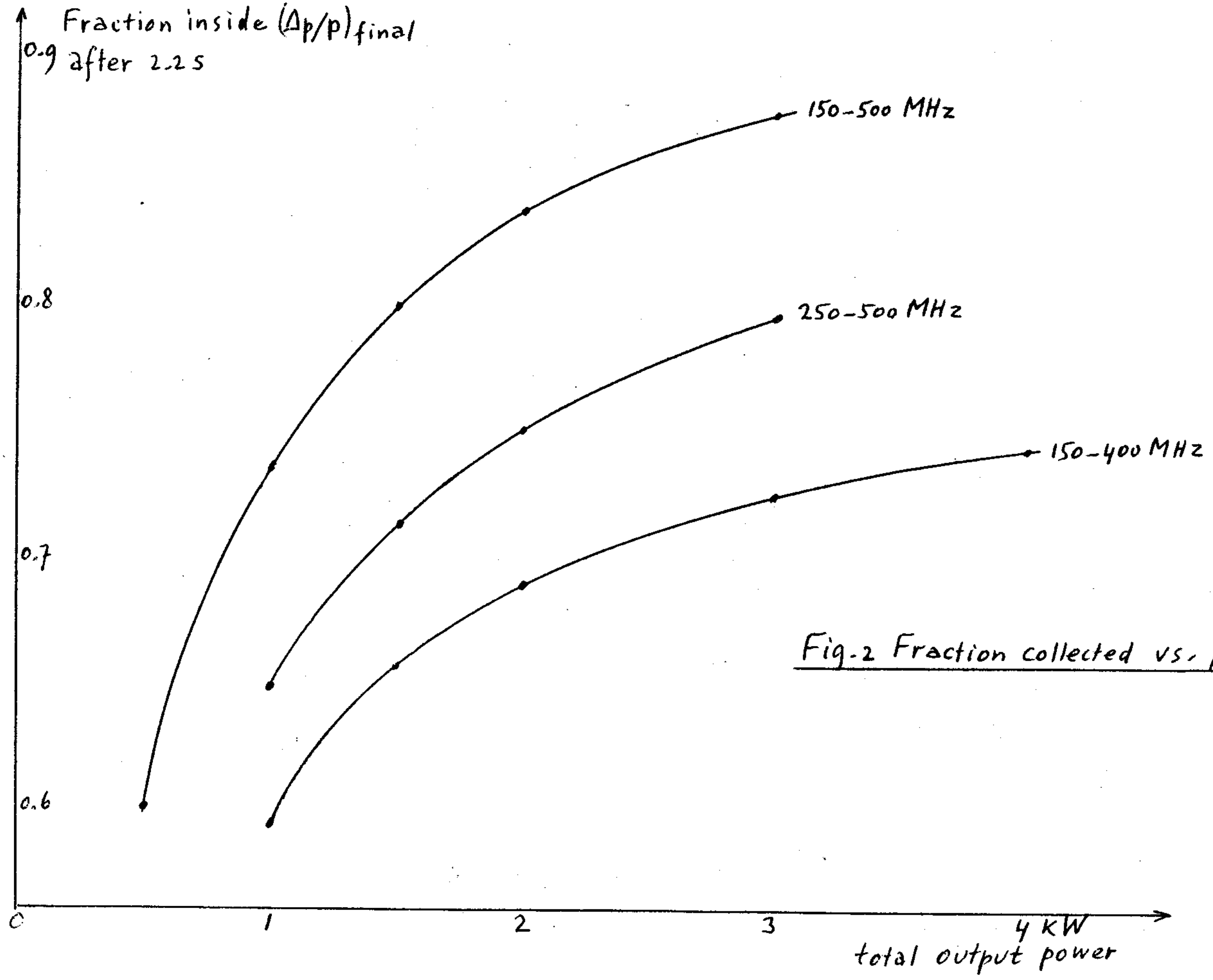


Fig. 2 Fraction collected vs. power

Fig. 3

Influence of intensity

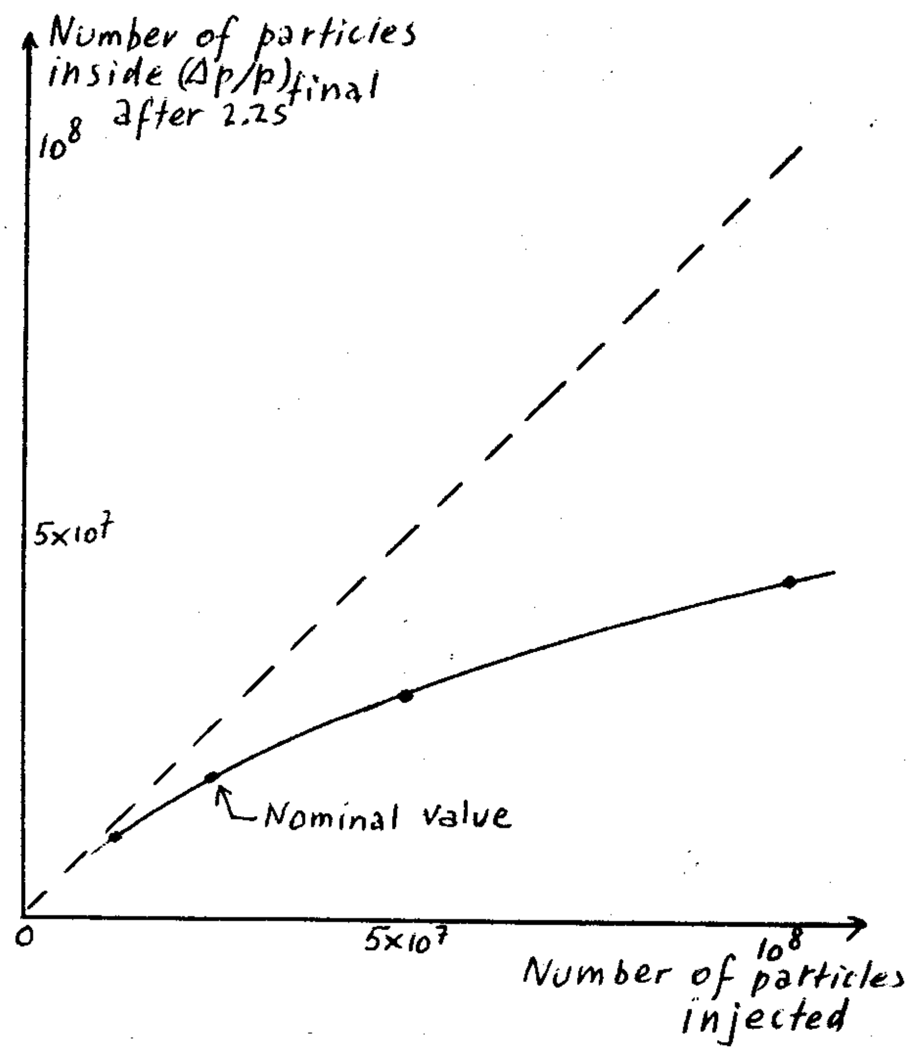
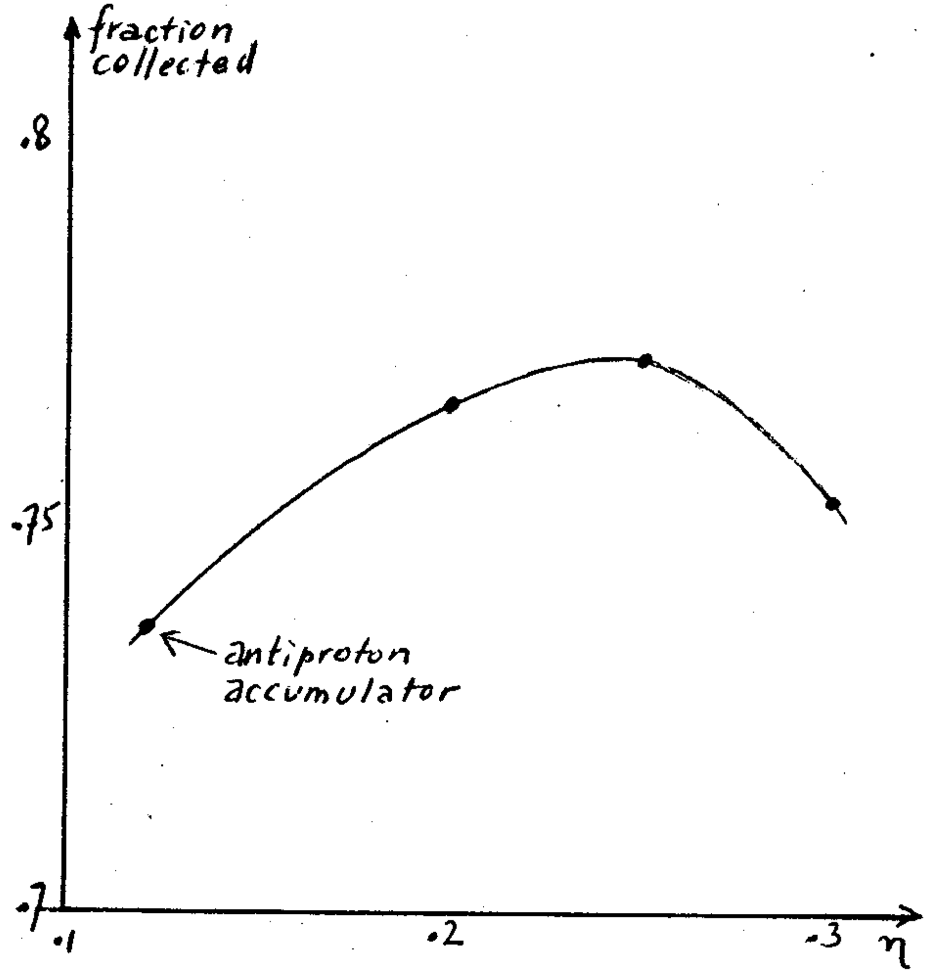


Fig. 4

Influence of η



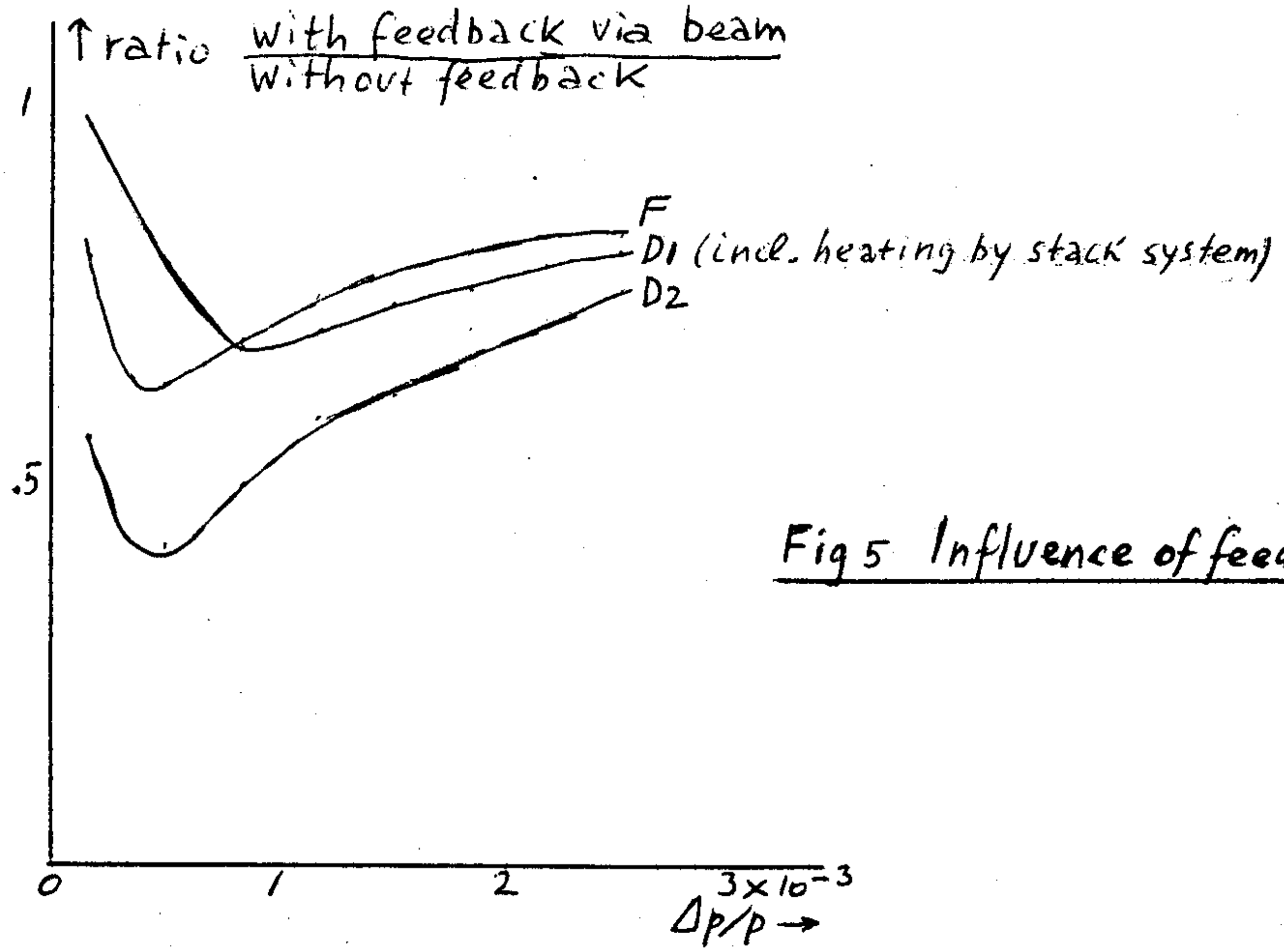


Fig 5 Influence of feedback

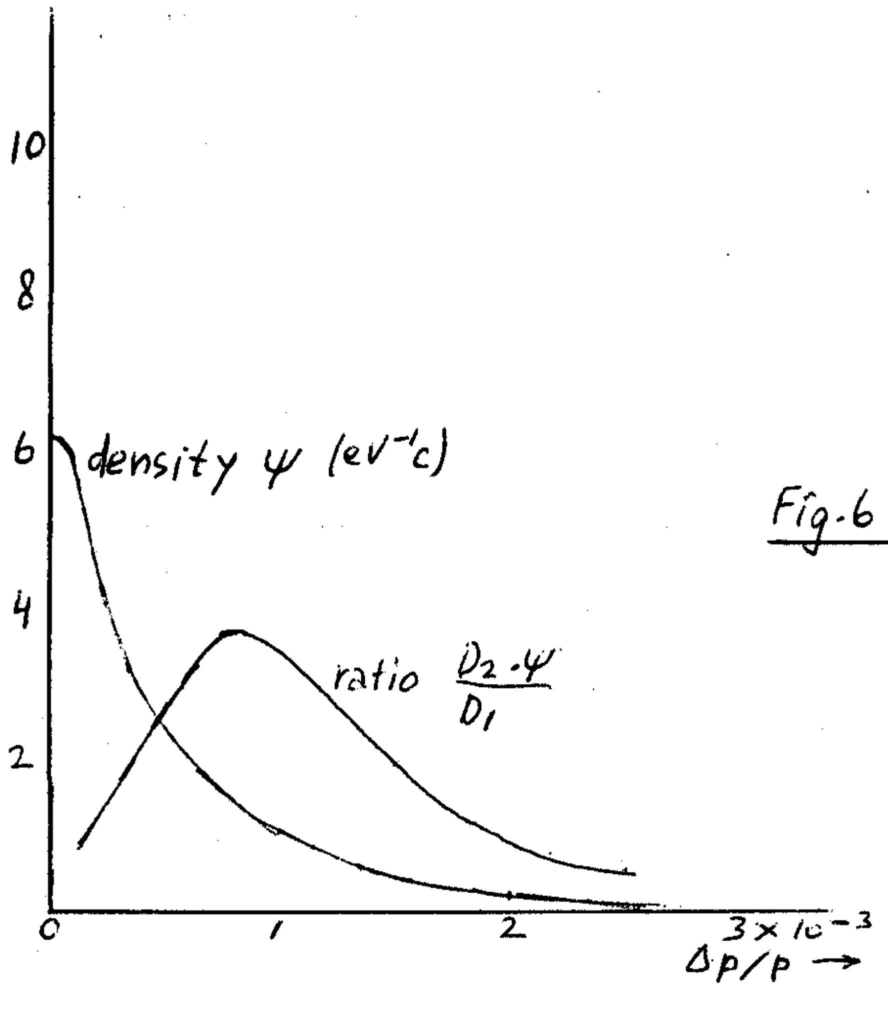


Fig. 6 Density and $\left(\frac{\text{Schottky}}{\text{amplifier}}\right)$ heating ratio