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SQUID BASED BEAM CURRENT METER

M. Kuchnir

INTRODUCTION

Superconducting QUantum Interference Devices (SQUIDs) have been used in medical research to measure the magnetic field created by the electric currents in the brain (1). Magnetoencephalograms have been produced with SQUIDs (2) since 1972. By using detecting coils sensitive to the gradients of the magnetic field this can be done without shielded rooms (3). What can these not so untested devices (invented around 1964 and commercially available in continuously improved versions since 1971) do for the measurement of antiproton beam current and beam position? Here we consider just the beam current meter.

THE SQUID

There are two kinds of commercially available SQUID systems: the rf SQUID with its single Josephson Junction and 19 MHz bias and the more sensitive dc SQUID with two Josephson Junctions and a small (approximately 1 μA) dc current for bias. Difficulty in making stable Josephson Junctions led to the early predominance of rf SQUIDs. From an engineering point of view J. Clarke (4) describes the principles of operation as follows: The dc SQUID consist of two Josephson Junctions in a superconducting loop of inductance L. See Fig. 1(a) .

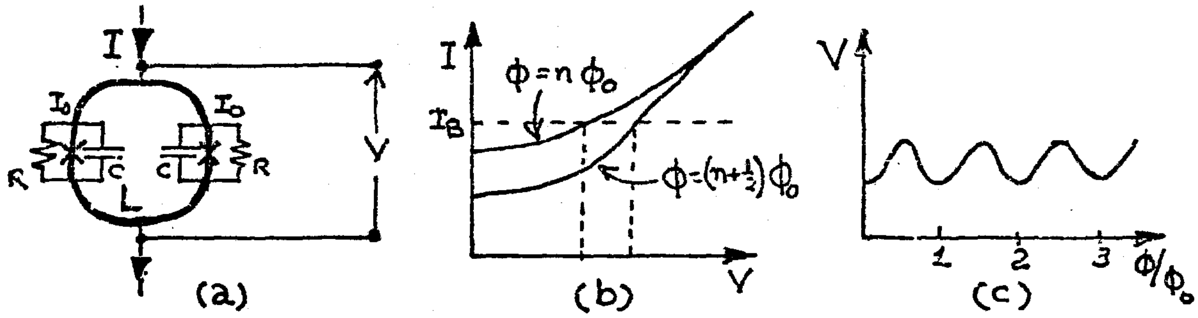

Fig. 1. (a) Configuration of dc-SQUID.
(b) Current-Voltage (I-V) characteristic with $\Phi=n\Phi_o$ and $(n+1/2)\Phi_o$.
(c) V versus Φ at constant bias current.

We assume that the junctions are ideal tunnel junctions each with a critical current Io and self-capacitance C. Each junction is resistively shunted to eliminate hysteresis on the current-voltage (I-V) characteristic. Fig. 1(b) show the I-V characteristics of the device with applied fluxes $\Phi=n\Phi_o$ and $\Phi=(n+1/2)\Phi_o$ threading the loop, where $\Phi_o=h/2e$ is the flux quantum (2.07E-15 Wb) and n is an integer. The critical current of the SQUID oscillates as a function of ϕ. The I-V characteristic is also a periodic function of ϕ, so that if one biases the SQUID with a constant current greater than the maximum critical current, the voltage across the device is as indicated in Fig. 1(c). For a flux near $(2n+1)\phi_o/4$, the SQUID is thus a flux-to-voltage transducer with a transfer function $V_\phi=(\partial V/\partial\phi)$. The equivalent flux sensitivity of the device is determined by dividing the rms voltage noise across the SQUID by V_ϕ to obtain the equivalent rms flux noise.

In practice, the SQUID is used as a null detector and may be operated in a flux-locked loop as indicated in Fig. 2.

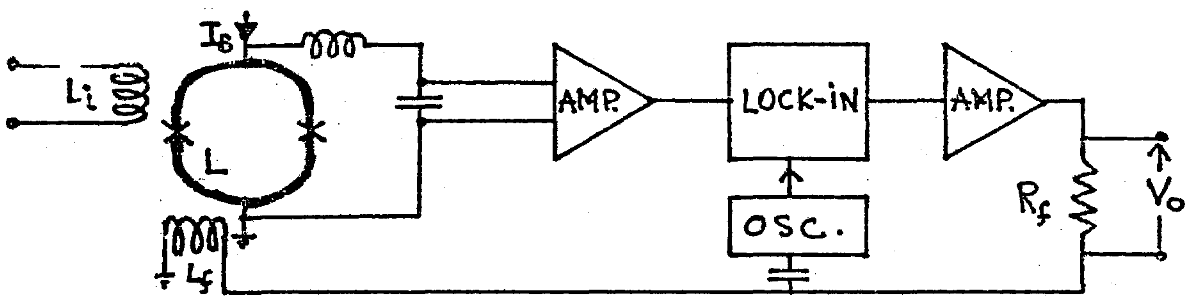

Fig. 2. DC SQUID in flux-locked loop.

An ac flux (typically at 100 kHz) with peak-to-peak amplitude $\phi_o/2$ is applied to the SQUID, and the resultant 100-kHz voltage is amplified by a cold LC resonant circuit or a cold transformer. If the average flux in the SQUID is $n\phi_o$ (Fig. 3(a)), the voltage across the SQUID is at 200 kHz. If the flux is increased or decreased from this value, a 100-kHz component appears in the voltage, with a phase that depends on the sign of the flux change (Fig. 3(b)). The 100-kHz signal is amplified and lock-in detected at the modulation frequency, as indicated in Fiq. 2.

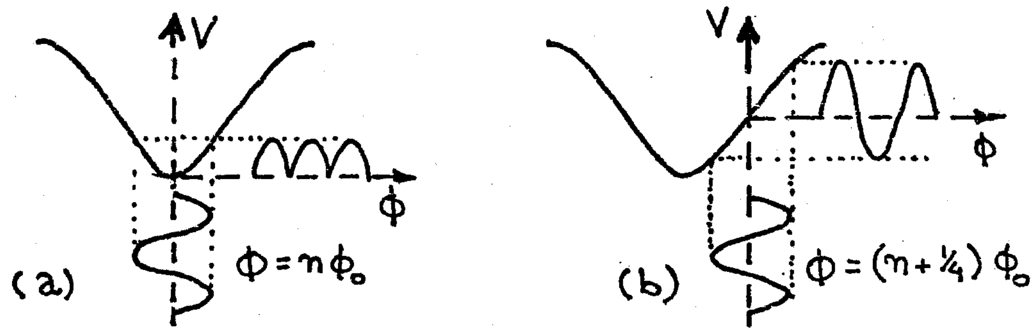

Fig. 3. Voltage across current biased dc SQUID produced by ac flux modulation with $\phi = n\phi_o$ and $(n+1/4)\phi_o$.

Thus the output from the lock-in is zero at $n\phi_o$, positive (say) for $\phi=(n+\delta)\phi_o$, and negative for $\phi=(n-\delta)\phi_o$, where $\delta \ll 1$. After further amplification, the voltage is connected across a resistor in series with the modulation/feedback coil coupled to the SQUID. Thus if a flux $\delta\phi_o$ is applied to the SQUID, the feedback current produces an opposing flux that cancels $\delta\phi_o$, the output voltage V_o being proportional to $\delta\phi_o$.

CHARACTERISTICS OF THE COMMERCIAL SQUID SYSTEM

In its most recent commercial version (S.H.E. Corp. model DBS) the SQUID system can be thought of as a black box with a superconducting input impedance of 2 μH that for a current of 200 nA through its input generates a full scale output voltage of 10 V with a 200 ohm output impedance. In its normal mode it responds from DC to 5 KHz and in its fast mode from DC to 50 kHz. The different modes corresponding to different time constants in the amplifiers and providing a trade between speed and stability. Because its output is a feedback to a very sensitive quantized phenomena the linearity is determined by Ohm's Law on the feedback resistor. The linearity can be further improved and the dynamic range greatly extended by automatically reseting the lock and counting the number of resets (6) with an up-down counter. Therefore keeping the feedback current small and the unit in its most sensitive scale. TTL compatible auto-reset and reset sign outputs for the up-down counter are included in the electronic control unit.

Its rms current noise is 1.5 $pA/\sqrt{Hz}$ for frequencies higher than 1 Hz ($.5/\sqrt{f}$ pA for frequencies below .01 Hz). That means that on observing slow accumulation rates with a reduced bandwidth of 1 Hz we can detect changes of 1.5 pA. For a storage ring with revolution period of 1.6 μs each antiproton contributes with .1 pA and this detectable change corresponds to 15 x 155 antiprotons at any current level !! (As will be seen further down the factor 155 comes from input attenuation needed for keeping lock under sudden 8 μA beam steps) This SQUID unit coupled with an up-down counter will form a beam current meter of unmatched sensitivity and range, an invaluable tool for diagnosing and fine tuning the stochasting cooling.

Although the SQUID itself is very fast, its feedback loop is not. In order to keep it locked sudden flux changes should be kept less than $\phi o/2$. Therefore the pickup impedance should be adjusted so that an 8 μA signal results in flux change of less than $\phi o/2$. This takes care of compatibility with the Debuncher beam. For sudden partial depletion of the Accumulator beam a low pass filtering inductor or eddy current shield (5) is needed at the SQUID input since the automatic reset takes time (35 μs). A 64 mA drop requires to uncount the accumulated 4129 counts (reset level set at 5 V, x1000 scale, each count corresponding to 1 ϕo or 15.5 μA beam current change). In order to get coverage for fast current changes a second pick-up with a SQUID operating in fast mode and in a less sensitive range could be incorporated in the same cryostat (6). The SQUID system comes with 4 sensitivity ranges, the least sensitive one handles at most .2 mA, i.e. a beam of .2 x 155 = 31 mA. A 64 mA drop in the Accumulator would involve 1.4 ms (4 counts).

Another possibility (7) in which all measurements can be done in the most sensitive scale, is to have incorporated in the pick-up a wire carrying a beam cancelling current. The circuitry needed for this external feedback comes included in the electronic unit. Of course one could also work with a less sensitive pick-up (a 1000 turn toroidal coil for instance) and the SQUID operating in the fast mode .

No saturation effects are expected. When the SQUID is cooled down, it traps the earth magnetic field in it (1.E-4 T) which for a typical area of 10 mm2 corresponds to a trapped flux of 1. nWb or 5.E+5 ϕo. A doubling of the number of fluxons corresponds to (.1 μA/ϕo)x 5.E+5 ϕo = 50 mA input current or 7.75 A beam.

THE BEAM CURRENT PICK-UP

An elegant way to transform the beam current into the current going through the SQUID system input is by means of a superconducting flux transformer consisting of a single loop of cylindrical geometry around the beam (8) as in Fig. 4.

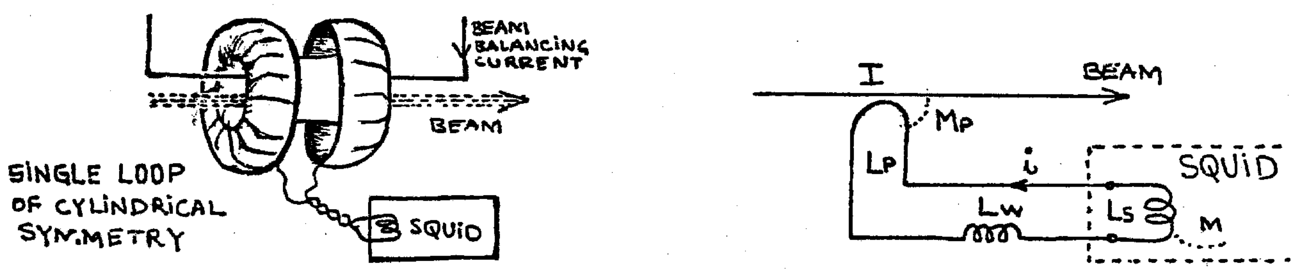

Fig. 4 Beam current detector concept and its pick-up circuit.

In such a transformer the current into the SQUID is independent of the beam cross-section or the beam position relative to the single loop.

If the flux, ϕ, due to the beam current I being prevented from getting into the primary (single turn toroidal coil) is $\phi = Mp \times I$, where $Mp \simeq Lp$ are the beam-single loop mutual-inductance and the single loop self-inductance. The current, i, that will flow through the SQUID input is

$$i = \phi/(Lp+Lw+Ls)$$

where Lw is the self-inductance of the twisted leads and Ls is the self-inductance of the SQUID input (2 μH). The flux that is actually detected by the SQUID and compensated by its feedback signal is

$$\phi s = M \times i \ ,$$

where M is the mutual inductance between Ls and the SQUID loop (20 nH). So the response of the system will be proportional to

$$\phi s = (Mp/(Lp+Lw+Ls)) \times M \times I \ .$$

If Lp $\simeq$ Mp are not much larger than Lw+Ls, we might need a transformer for optimum impedance matching to the SQUID. Let us estimate Lp and Lw: The magnetic field at a distance, r, from the beam is

$$H = (\mu_o/2\pi) \times I/r$$

the energy being excluded by Lp is

$$.5 \ Lp \ I \ I = \ .5 \ \mu/\mu_o \int H \ H \ dv$$

substituting and integrating from the inner radius, a, to the outer radius, b, for a length, c, we get

$$Lp \ I \ I = \mu/\mu_o \int_0^c \int_0^{2\pi} \int_a^b (\mu_o^2/4\pi^2)(I/r)^2 \ r \ dr \ d\theta \ dz$$

for $\mu = 1$

$$Lp = (\mu_o / 2\pi) \times c \times \ln(b/a)$$

which for a = 3 cm, b = 6 cm and c =10 cm yields Lp = .014 μH. The inductance for a pair of wires of length s cm, diameter t cm, with centers appart by d cm is (9):

$$Lw = .004 \times s \times (\ln(d/t) + .25 - d/s) \quad \mu H$$

which for s = 10 cm, d =2t and t = .02 cm yields Lw = .017 μH.

We therefore conclude that with $Mp \simeq Lp$ and without a matching transformer the pick-up considered (6 cm i.d., 12 cm o.d., 10 cm long) will result on

$$i = I / 145 \quad .$$

The condition for keeping lock under a sudden excursion of 8 μA is $\phi s \leq \phi o/2$. Neglecting the mutual inductance to the shield as we have done so far this translate into

$$Lw = (Lp \times M \times I / (\phi o/2)) - Lp - Ls$$

$$Lw = 14.E-9 \times 20.E-9 \times 8.E-6/(.5 \times 2.07E-15) - 14.E-9 - 2.E-6 \ H$$

$$Lw = 151. \ nH$$

and the ratio between the beam current I and the input current i becomes

$$i = 14 \times I / (14+151+2000) = I / 155 \quad .$$

THE SUPERCONDUCTING SHIELD

This pick-up system has to be shielded from extraneous magnetic fields. Therefore a superconducting beam pipe containing the single loop in its center and a superconducting tubing around the twisted leads as shown in Fig. 5 are required.

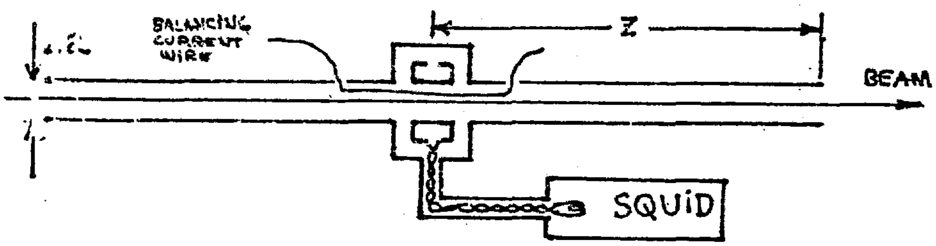

Fig. 5 Longitudinal cross-section of properly shielded beam current detector.

How long should a 60 mm diameter shielding pipe be to reduce the influence of an .01 Tesla external field to the order of the field due to a 1.5 pA beam?

In a superconducting cylindrical shield of radius a the magnetic field H at a distance z>>a from the extremity falls off as (10) :

$$|\vec{H}|_{axial} \propto e^{-3.83\, z/a}$$

$$|\vec{H}|_{transverse} \propto e^{-1.84\, z/a}$$

Therefore:

$$H = (\mu_o/2)\ I/a \simeq .01 \times \exp(\ -1.84\ z/a\ )$$

$$3.E{-}17/\ a \ \simeq\ \exp(\ -1.84\ z/a\ )$$

for $a = .03$ m we get $1.E{-}15 \simeq \exp(\ -61.33\ z\ )$ or $z \simeq .56$ m

Answer: $2z \simeq 1.13$ m

The mutual inductance between the pick-up and the shield will affect the relationship between the beam current and the SQUID input current. The quantitative value of this relation can be best determined by measurements in small prototypes (11). These small prototypes can be made out of lead and will permit evaluation of almost all other properties of the system before building the cryostat.

RADIATION

Provided that the level of radioactivity doesnt heat up the superconducting components above their critical temperature, it does not affect them adversely. Actually, type II superconductors can have their critical current increased by irradiation. A SQUID, protected by some lead shielding, at a few centimeters from the beam tube would probably operate without problems. The materials involved in the SQUID probe (Nb, NbTi, BeCu, Brass, Si, SiO_2, G-10, solder and some epoxy) are not particular sensitive to radiation. The SQUID electronics can be located 100 m away.

CRYOGENICS

Tests on a 30cm long prototype can be made with existing equipment. The shield requirements might be less than the calculated above (11) but if it turns out that 1.13 m long shield is actually needed, a special cryostat will have to be designed and built. Fig. 6 is a conceptual schematic of such a cryostat with some typical dimensions and features indicated.

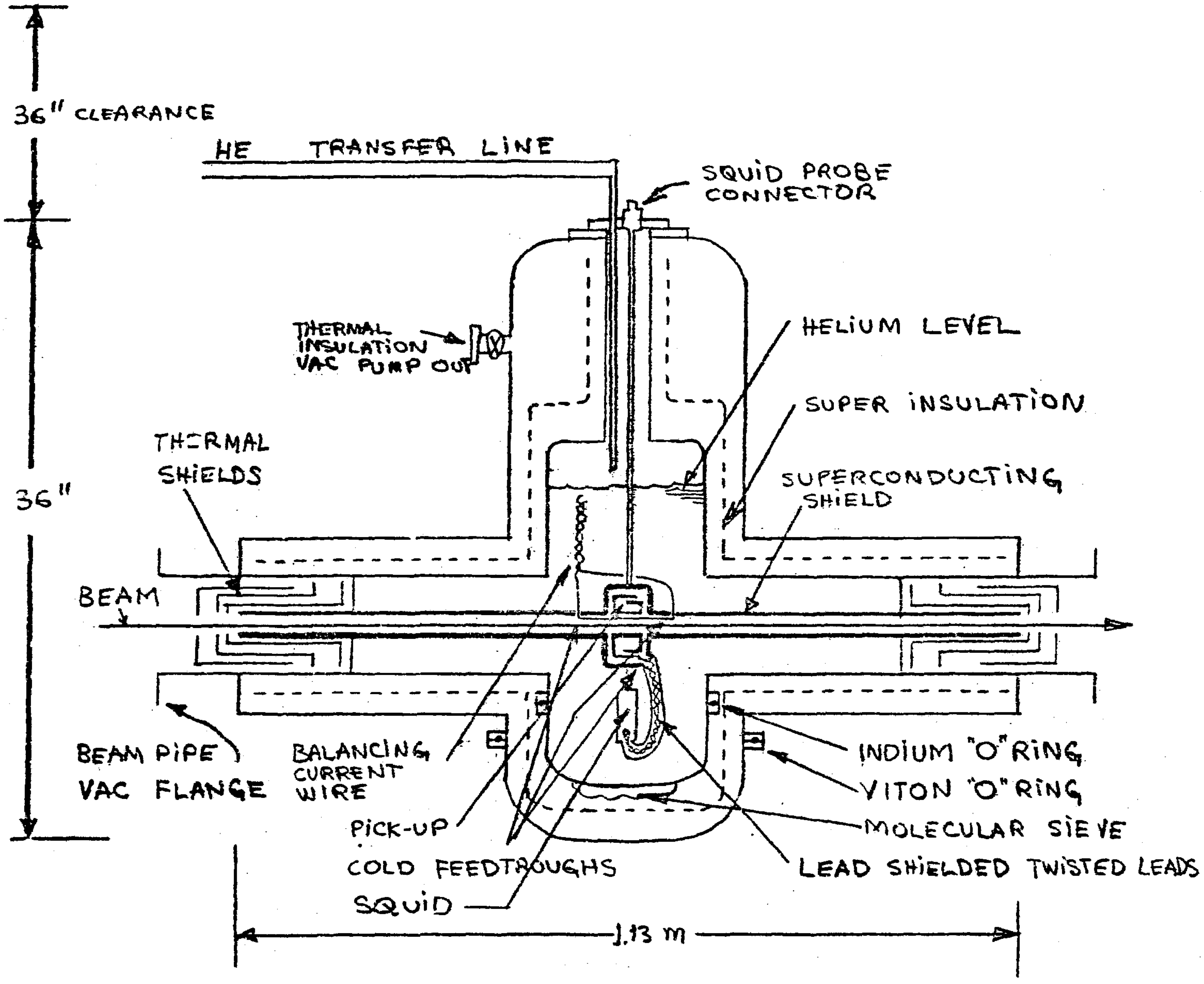

Fig. 6 Beam current meter cryostat.

With proper design the heat load of this cryostat can be kept below 1 or 2 watts if the superinsulation and thermal shields are properly applied. The reliability of the unit from the cryogenic point of view should be better than an Energy Saver magnet (no quenches or QPM misfirings). For the satellite refrigerator assigned to the project it is a trivial load, which nevertheless will require installation of transfer lines. It could however be designed for a once-a-week fill-up from a storage dewar.

Not indicated in Fig. 6 are features related to temperature stability. The critical current in the SQUID depends on temperature. For the S.H.E. Corp. rf SQUID the zero drift due to temperature change is less than 10 nA/K. Probably a similar number is true for its dc SQUID. The Helium bath pressure between filling operations is probably stable within .3 psi corresponding to .01 K or a drift of .1 nA. Rather simple pressure or temperature controllers added to the cryostat can reduce this drift even further.

R & D COST AND SCHEDULE

Except for the 13.8 k$ SQUID practically all the equipment needed for testing 1/5 size lead prototypes is available.

SQUID Procurement: 3 months

Prototype development: 2 months

Cryostat design and fabrication: 6 months + 15 k$

COMPARISON WITH AA CURRENT TRANSFORMER

The following table is based on K. Unser (12) description and a SQUID pick-up with input current = beam current / 155.

Parameter	AA Transformer	SQUID meter
Resolution (5 Hz)	1 μA	1 nA on top of 64 mA based on 13 dB signal to noise and discontinuities < 8 μA
Linearity	.001%	.001% ?
Zero Drift (24 hours)	3 μA	15.5 nA without temperature controller
Long term stability	.0005% full scale	15.5 nA without temperature controller
Residual ripple	5 μA rms	.52 nA rms noise
Freq. range	dc-50 kHz	dc-5 kHz normal mode dc-50 kHz fast mode
Current ranges	0-50 mA	0-.2, 2, 20, 200 mA
	0-500 mA	Any range usable with cancelling current or updown counter

SUMMARY

A SQUID based beam current meter has the capability of measuring the current of a beam with as little as 30 x 155 antiprotons (with a signal to noise ratio of 2). If low noise dc current is used to cancel most of the beam or an up-down counter is used to count auto-resets this sensitivity will be available at any time in the accumulation process. This current meter will therefore be a unique diagnostic tool for optimising the performance of several Tev I components. Besides requiring liquid helium it seems that its only drawback is not to follow with the above sensitivity a sudden beam change larger than 16 μA, something that could be done using a second one in a less sensitive configuration.

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