REPORT CTSL-**24**

VACUUM REQUIREMENTS FOR THE CASCADE SYNCHROTRON

VINCENT Z. PETERSON

APRIL 11, 1961

SYNCHROTRON LABORATORY

CALIFORNIA INSTITUTE OF TECHNOLOGY

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Contents

Acknowledgments

I wish to thank especially Dr. M. H. Blewett for providing unpublished data on the design and performance of the Brookhaven A.G.S. vacuum system.

I Introduction

This report is an examination of the principal characteristics of a vacuum system for the proposed 300 Bev cascade synchrotron[1). In particular, we wish to see whether the small aperture and large circumference of the Main Ring present vacuum difficulties. Gas scattering losses, eddy currents in the vacuum chamber wall, and cost of a 5-mile vacuum system are of special interest.

Attention has been directed primarily toward the Main Ring. The 10 Gev Booster Ring[1) has vacuum requirements similar to existing accelerators, and it is presumed that duplication or modification of such vacuum systems will be practical. Our concern here is to see that no major problem is ignored, and to obtain representative numbers for a possible design.

A recent proposal has been to employ multiple-pulse injection from the Booster Ring (30 pulses over 3 seconds); the Main Ring would be kept at constant injection field for a storage time of 3 seconds before acceleration commences. The gas-scattering during this "storage mode" places much more stringent requirements upon a good vacuum than the normal "acceleration period" of 1 second. Average pressures of 10^{-6} mm. Hg are needed if 3-second storage is employed; 10^{-5} mm. Hg seems sufficient for 1-second acceleration.

The high injection energy reduces gas scattering and thus offsets most of the vacuum limitations of the small aperture. A small vacuum chamber can have thin walls, and thus eddy current effects are small; the moderate rate-of-rise is also important. In the following paragraphs a feasible vacuum system is outlined (for both "storage" and "acceleration" modes). Specific calculations of gas-scattering eddy currents, pumping speeds, etc., are given and show that the vacuum problems are manageable.

Ionic pumps of the discharge-type seem very suitable to this machine. They are non-contaminating, and fail-safe, and thus do not

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1) Report CTSL-10, "A Proton Synchrotron for 300 Gev", by Matthew Sands.

require extensive valving or interlocks. Largely due to such simplifications, and a combined pole-tip-and-vacuum-chamber mass production assembly, it is estimated that the vacuum system will cost $3-4 million (instead of $6 million, the first extrapolation from Brookhaven's A.G.S.).

II General Considerations

The fundamental requirement of the vacuum chamber is to provide a low-pressure region of sufficient horizontal and vertical aperture to accommodate the expected particle oscillations with negligible loss. Gas scattering must not significantly increase the initial amplitudes of injection.

The vacuum chamber should not disturb the shape of the guide field, so that complicated magnetic field corrections are required. Eddy current effects should be minimized. It is desirable to avoid having to provide pole-tip windings.

One would like a simple design, which can be constructed with standard fabrication procedures, since the Main Ring involves 1200 sections. We have preferred an all-metal construction, avoiding plastics, because of the better outgassing, radiation damage, and mechanical properties of metal.

The pumping system would ideally require only a small number of pumps which could maintain low-pressure with long-life, trouble-free operation. Failure of a single pump should not suspend machine operation, nor should it cause system contamination. A minimum of valves, interlocks, and remote controls is desirable; however, a monitoring system for pressure and pump-functioning will undoubtedly be required.

III Choice of Vacuum Chamber Dimensions

(A) Aperture requirements

Estimated useful magnetic aperture requirements for the Main Ring are[1]:

a = radial aperture = 50 mm.

b = vertical aperture = 20 mm.

These are peak-to-peak values, and include not only the expected initial injected betatron oscillation amplitudes but also increases in amplitude due to errors in magnet alignment, etc.

The initial amplitude of betatron oscillations in the vertical plane is important in estimating gas-scattering losses in the "storage mode". The estimated injected beam dimensions in the main ring[2] are:

b_i = 1.7 cm (vertical)

a_i = 3.0 cm (radial)

(B) Assumed vacuum chamber and pole tip dimensions

In order to make specific calculations of various effects, we have scaled the dimensions of our vacuum chamber from that of the Brookhaven A.G.S. If the actual inside dimensions of the elliptical vacuum chamber are A(radial) and B(vertical), whereas the useful magnetic apertures are $a \times b$, then we assume that the ratios A/a and B/b remain constant. A cross sectional view is shown in Fig. 1.

In Table I the relevant dimensions of the A.G.S., the CERN Proton Synchrotron (PS), and our proposed Cascade Synchrotron (CS) Main Ring vacuum chambers are summarized.

The vacuum chamber wall thickness (t) is also given. Experiments at Brookhaven with ribbed walls showed that the A.G.S. chamber could be as thin as 0.055", but the final choice was a somewhat thicker (0.078") unribbed wall to simplify construction. The proposed CS chamber has smaller linear dimensions by a factor of about 2.5, and the wall thickness has been reduced in the same ratio. It should therefore withstand atmospheric pressure as well as the A.G.S. chamber.

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2) See page 5 of Report CTSL-16, "Beam Transfer in the Cascade Synchrotron", by R. L. Walker.

TABLE I.

VACUUM CHAMBER DIMENSIONS

		Brook AGS	CERN PS	CS (Main Ring)	
Magnetic aperture (radial)	a	120	--	50	mm.
Magnetic aperture (vertical)	b	50	--	20	mm.
Vacuum aperture (radial)	A	178	150	78	mm.
Vacuum aperture (vertical)	B	83	70	31	mm.
Vacuum chamber wall	t	.078"	.079"	.034"	inches
Magnet gap, center	g	89	100	37	mm.
Magnet section length	ℓ	10	--	22	feet
Chamber-magnet clearance	δ	1.6	6	1.6	mm.
Pole-face windings		No	Yes	No	

The minimum magnet gap (at the center of the aperture) permitted by this vacuum chamber is 37 mm. It is assumed that no pole-face windings will be required; the discussion of eddy-current effects will show that the CS should have less reason than the AGS for pole-face windings (and the AGS has worked successfully without them).

The above dimensions allow a minimum clearance, δ, between exterior of vacuum chamber and magnet pole-face of about 1.6 mm. This figure was chosen to be the same as for the AGS machine. Even this clearance may prove unnecessary, in the absence of pole-face windings, since the median plane should be very well-determined by pole-tip geometry. The present thought is to assemble the vacuum-chamber and magnet unit as an integral unit, and adjust only section blocks.

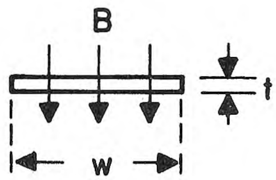
The circumference of the CS Main Ring (5.0 miles) divided by the number of magnet sections (1200) is 22.2 feet, the average length of a vacuum section. Although detailed design may require some sections of different length, this average figure will be used in pumping speed calculations.

IV Eddy Currents in a Metal Vacuum Chamber

We will examine only a portion of the eddy current problem, namely, eddy currents induced in the vacuum chamber walls by the varying magnetic field at time of injection. Other eddy currents close to the beam could be induced in pole-tip laminations, magnet windings, and pole-face windings (if such were required). If eddy currents in the vacuum chamber are small, then pole-face windings will probably be unnecessary.

A thin chamber wall (of high resistivity naterial), a high injection magnetic field, and a low rate-of-rise are desirable to minimize eddy current depression of the guide field and distortion of the field gradient. Fortunately, in the Cascade Synchrotron the parameters chosen[1)] give very small eddy current effects, especially if the CS follows the AGS practice of using a smaller dB/dt at injection than later in the cycle. In this case, one can dispense with pole-face windings, saving magnetic aperture and greatly simplifying vacuum-chamber-and-pole-tip assembly.

In order to display the dependence of eddy current fields upon important parameters, consider a single long, flat sheet of resistivity ρ, width w, and thickness t in a changing magnetic field B(t) normal to the plate. Then at the center of the plate,



$$\delta B = \frac{\mu_o}{2\pi} \frac{wt}{\rho} \frac{dB}{dt} \quad \text{(m.k.s. units)}$$

where δB is the eddy current depression of the field. Note the linear dependence upon width and thickness, as well as upon rate-of-rise (the length of the strip is unimportant). More refined calculations must of course take into account the exact shape of the chamber, and the considerable variation of dB/dt (~ 30 per cent) across the width of the chamber. The variation of dB/dt will produce a change in δB with radial position, and will thus affect the gradient of the field, dB/dr. These effects must be carefully calculated before final design.

For the present, it is sufficient to make an extrapolation from the Brookhaven AGS experience since the chambers are similar. Table II summarizes the eddy current data from Brookhaven and estimates for the Cascade Synchrotron:

TABLE II

VACUUM CHAMBER EDDY CURRENT EFFECTS
(Inconel X, ρ = 120 μ ohm-cm)

	Brook. AGS	Proposed CS	
Injection field, center, B_i	120	300	gauss
Radial magnetic aperture, a	12	5	cm.
Variation in B_i across a, $\lvert\Delta B_i\rvert = n \frac{B_i}{R} a$	40	99	gauss
Fractional variation, $\Delta B_i/B_i$	0.33	0.30	

	Brook. AGS	Proposed CS	
Rate-of-rise of magnetic field:			
At injection, dB_i/dt	3	3	kg/sec.
Acceleration, dB/dt	12	12	kg/sec.
Vacuum chamber:			
Width	17.8	7.8	cm.
Wall thickness	.078"	.034"	inches
Eddy current δB_i at injection:	1.0	0.18	gauss
$\delta B_i/B_i$	0.008	0.0006	
Eddy current change in field gradient:			
Outer edge of aperture	11	2	per cent
Inner edge of aperture	-3	-0.6	per cent

The Brookhaven data are based on calculations by Blewett, "fairly closely corroborated by measurements made later by the magnet group"[3]. The extrapolation to the CS is based on the above eddy current formula; i.e., due to a thinner and narrower vacuum chamber, the eddy currents are five times less in the CS. (Assuming the vacuum chamber to be 2 parallel plates, the above simplified formula gives $\delta B_i = 0.68$ gauss --- vs. 1.0 gauss measured --- for the AGS. If wall curvature was considered, the agreement would be even closer.)

Note that both machines have essentially the same fractional space variation of field across the useful radial aperture (30-33 per cent). With the same rate-of-rise of injection field, this means that the fractional change in field gradient (change in $\left|1/B \cdot dB/dr\right| = n/R$) due to eddy currents will also be a factor of 5 lower than the AGS.

Thus the proposed CS all-metal vacuum chamber, in a 3 kilogauss/second rising field, would depress the central guide field 0.2 gauss, and after field gradients by a maximum of 2 per cent.

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3) M. H. Blewett, private communication.

Guide field depression is of little concern unless it varies from section to section, due to variations in the resistance of individual chamber sections. Brookhaven required uniform resistivity (within 3 per cent) of the Inconel sheet stock and assembled chamber sections, in order to keep variations in the injection field less than 0.1 per cent, or 0.12 gauss. For the CS this is trivial since the entire effect is less than 0.1 per cent.

The variation in field gradient (or in _n_) is also probably not serious. The CS specifications[4] call for a stop-band width of 0.1, which requires maintaining _n_ within 1 per cent on all magnets. The vacuum chamber eddy currents can produce a shift in _n_ of -0.6 per cent to +2 per cent across the radial aperture; however, the average _n_ per section will be less disturbed, and variations from section to section should be even smaller.

We conclude that the thin-wall all-metal vacuum chamber will produce even fewer eddy current problems than the Brookhaven AGS chamber. However, before relaxing requirements on a low rate-of-rise at injection, further study of the effects of eddy currents on _n_ should be made.

V Gas Scattering

The presence of gas in the vacuum chamber results in multiple scattering, single-scattering, and nuclear interactions of the protons. The thickness of gas traversed in 1 second is ~ 0.5 gm/cm^2 at a pressure of 10^{-5} mm. Hg, so that nuclear interactions do not constitute a serious beam loss. Single scattering losses are negligible compared with multiple scattering losses; for 10 Gev protons in air, the r.m.s. Rutherford scattering angle (.012 milliradians) is much less than the loss angle (vertical semi-aperture/betatron wavelength) of 0.52 milliradian.

A rough idea of the effects of gas scattering may be obtained by

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4) See page 22 of Reference 1.

calculating the r.m.s. plane-projected scattering angle for protons in air:

$$\alpha = \left\langle \theta^2 \right\rangle_{PP}^{1/2} = \frac{1}{\sqrt{2}} \frac{21}{E} \sqrt{x} \qquad \text{(radians)}$$

where E = 10 Gev and x = 1190 pt is the radiation length traversed in time t at pressure p (mm. Hg). When multiplied by the betatron reduced wavelength ($\lambdabar$ = 30 meters), the resultant amplitude b may be considered as the contribution due to multiple scattering. At 10 Gev and 10^{-5} mm. for 1 second,

$$\alpha = 0.16 \text{ mrad.}$$

$$b = \lambdabar\alpha = 0.49 \text{ cm.}$$

Assuming a Gaussian distribution of r.m.s. half-width b, a vertical semi-aperture $\frac{1}{2}$ B = 1.55 cm., zero initial betatron amplitude, and no damping due to acceleration, one can readily calculate that 99.8 per cent of the protons will not strike the walls. However, for 3 seconds storage at 10^{-5} mm. Hg the survival probability P(p) drops to 93.7 per cent. In Fig. 2 the curve labeled "Gaussian" gives survival probability as a function of pressure for 3-second storage.

A more exact treatment, using diffusion theory, is given by Courant[5]. The effect of initial betatron vertical oscillation amplitude (Z_i), and of damping during acceleration are taken into account. The survival probability is given by:

$$P(\eta) = 2 \sum_{s=1}^{\infty} \frac{J_0(\lambda_s \beta)}{\lambda_s J_1(\lambda_s)} e^{-\lambda_s^2 \eta}$$

5) E. D. Courant, R.S.I. 24, 836 (1953); Blackman and Courant, Phys. Rev. 75, 315 (1949).

where

$$\eta = \frac{1}{2}\left\langle b^2 \right\rangle / Z_m^2$$

Z_m = vertical semi-aperture = $\frac{1}{2}$ B

$Z_i = \beta\, Z_m$ = initial amplitude of betatron oscillation

$\left\langle b^2 \right\rangle$ = mean-square amplitude of vertical oscillation induced by multiple scattering

λ_s = $s^{\underline{th}}$ root of $J_o(x)$

The values of $\left\langle b^2 \right\rangle$ are determined from:

$$\left\langle b^2 \right\rangle = \frac{1}{2}\,\bar{\lambda}_b^2 \left\langle \theta^2 \right\rangle_i N\sigma_i \cdot x = \frac{1}{2}\,\bar{\lambda}_b^2 \left\langle \theta^2 \right\rangle_i (x/\lambda_i)$$

where

$\bar{\lambda}_b$ = betatron wavelength (reduced) = 30.0 meters

$\lambda_i = (N\sigma_i)^{-1}$ = mean-free-path for scatter (angles θ_{min} to θ_{max}) at the injection momentum p_i

$\left\langle \theta^2 \right\rangle_i$ = mean-square single scattering angle (between limits θ_{min} and θ_{max} determined by screening and nuclear size)

and the distance x depends upon machine operation.

Case I ("storage"). No damping.

$x = ct$ = actual distance travelled in accelerator.

Case II ("acceleration"). Damping with eV energy gain per turn and T_i injection energy. $x = \frac{1}{2}\, x_2$, where $x_2 = 2\pi R\; T_i/eV$ is the distance travelled in doubling the injection energy (about 1250 turns or 10^7 meters).

Figure 2 shows the survival probability as a function of pressure for three situations:

(a) Case II. Acceleration with 8 Mev/turn acceleration. Due to rapid damping, the gas scattering losses are negligible out to pressures of 10^{-3} mm. (However, nuclear interactions, ionization, and other effects make such a high pressure undesirable.)

(b) Case I, with $Z_i = 0$. Storage for 3 seconds, with zero initial betatron amplitude. This compares most directly with the simplified Gaussian calculation.

(c) Case I, with $2Z_i = 1.7$ cm. Storage for 3 seconds, with initial betatron amplitude as expected from Booster Ring. This situation represents 30-pulse injection. The long storage time requires pressures $\leq 1\text{-}2 \times 10^{-6}$ mm. to reduce gas scattering.

We conclude that $\leq 10^{-5}$ mm. average pressure will be required if single-pulse acceleration is adopted, whereas $\leq 1 \times 10^{-6}$ mm. will be necessary for 3-second storage.

VI Pumps

The small aperture of the Main Ring vacuum chamber means that the chamber limits pumping speed; conversely, only small pumps can be usefully employed. However, this is not a real disadvantage since the configuration of the accelerator lends itself to local units (rather than a few centralized pumping stations). Emphasis is on clean, uncontaminated, baked-out vacuum sections, using the new discharge-type ion pumps. These pumps have additional desirable features of fail-safe operation, self-gauging, and absence of contaminating fluids.

(A) Section Conductance; Outgassing Sources

The molecular-flow conductance of an elliptical 3.1 cm. x 7.8 cm. section of length $\ell = 680$ cm. (22.2 ft.) is:

$$C_o = 12 \frac{d^3}{\ell} = 3.6 \text{ liters/second}$$

where d = 5.9 cm. is the equivalent diameter of a circular tube. (Each Brookhaven AGS section has a conductance of ~ 100 lps.) This low conductance of a CS section means that only small capacity pumps will be useful.

With long, small-aperture tanks it is important that outgassing sources (especially at mid-section) be minimized. An all-metal chamber has advantages over chambers involving plastics in this respect. Probably an all-metal chamber can be baked-out and sealed-off prior to assembly of magnet sections, thereby reducing outgassing significantly.

Brookhaven's experience with the AGS vacuum system[3,6] provides us with some outgassing data. The rate-of-rise of pressure in 5" diameter tubing (previously degreased and sandblasted but not baked-out) was 8×10^{-6} mm. Hg per minute. Assuming the source to be outgassing from the walls, one obtains

$$Q/\text{area} = 0.33 \times 10^{-6} \text{ micron-liter/sec/cm}^2$$

We shall use this figure in estimating pumping requirements. However, it should be borne in mind that at least two possibilities exist to lower this figure, namely (1) bake-out procedures, and (2) the distribution of outgassing sources is probably such that it is lower in mid-section and higher at section ends (where gaskets, flanges, etc., exist).

(B) Minimum Pump Spacing

We make the following assumptions in order to estimate the minimum distance between pumps to achieve a desired mean pressure $\bar{p}$ in the vacuum chamber:

1) Outgassing is uniformly distributed along the chamber.
2) The speed of the pump will be sufficient to maintain a pressure at the pump inlet much lower than the mean pressure in the chamber ($p_i \ll \bar{p}$).
3) The resultant pressure variation along the chamber is linear, reaching a peak midway between pumps.

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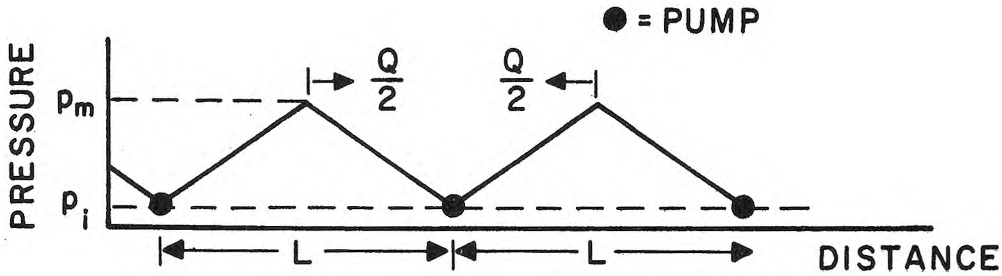
6) BNL-3745, "Vacuum System for a 25 Bev Particle Accelerator", C. L. Gould.

Schematically the situation is as shown:



The average pressure is thus $\bar{p} = \frac{1}{2}(p_i + p_m) \approx \frac{1}{2} p_m$.

Each pump must remove an amount Q of gas per second from a total length L of chamber, so that

$$Q = 4C_L (p_m - p_i) \approx 4C_L \cdot p_m = 48 \frac{d^3}{L} p_m$$

where p_m is in <u>microns</u>, C_L is the conductance (in lps) of a tube of diameter d (cm.) and length L (cm.). (The factor of 4 arises from the fact that each pump evacuates L/2 on each side.) The sources of gas are the tube walls:

$$Q = \pi dL\,(0.33 \times 10^{-6})$$

Thus the average pressure (in microns) is:

$$\bar{p} = \frac{1}{2} p_m = 1.1\,(L/d)^2 \cdot 10^{-8}$$

Typical values are given in Table III.

TABLE III

PUMP SPACING vs. PRESSURE

(ℓ_o = 22.2 feet = 6.8 m. = 1 section)

L/ℓ_o	$\bar{p}$ (mm. Hg)
1	0.13×10^{-6}
2	0.52×10^{-6}
5	3.3×10^{-6}
10	12.7×10^{-6}

The conclusion is that with a clean, all-metal vacuum system of equivalent diameter 5.9 cm., the pump spacings required would be:

<u>3-second storage</u>: $\bar{p} \leq 2 \times 10^{-6}$ mm.
$L = 3\ell_o$ (every 3rd section)
No. of pumps = 400

1-second acceleration: $\bar{p} \leq 2 \times 10^{-5}$ mm.
$L = 10\ \ell_o$ (every 10th section)
120 pumps required

(C) Type of Pumps

It is proposed to use the newly-developed discharge-type ionic vacuum pumps. The ionic pump has numerous advantages over the old-style diffusion pump, namely:

1) no working fluid; hence, no contamination of the vacuum system by backstreaming;
2) "fail-safe" operation; eliminates need for fast-action valves;
3) when roughed below ~ 30 microns, does not require forepump; no traps, baffles needed;
4) high pumping speeds down to 10^{-8} mm. These features make ionic vacuum pumps particularly suited to high-energy accelerators.

The Brookhaven AGS uses the earlier type of ion-pump, the "Evaporion" pump, which operates by evaporating titanium to trap gas molecules while condensing on a nearby wall. The AGS uses 48 of the 1900 lps Evaporion pumps. The pumping speed of titanium evaporation pumps is not as high for inert gases as it is for active gases (H_2, N_2, O_2).

The newer discharge-type ion-pumps use a high-voltage discharge in a magnetic field to increase the ionization path, in the manner of a Penning gauge. Titanium is employed to remove active and inert gas atoms by chemical combination, sputtering, and evaporation. The pumping speed is high for all gases down to 10^{-8} mm. Units are made commercially by CEC, Varian and Ultek with pumping speeds from 30 lps to 100,000 lps.

The operating "life" of the discharge-type is at least 10^4 hours at 10^{-6} mm. after which time the sputter cathode must be replaced.

Since ion-pumps require auxiliary pumps only above 30 microns, it is feasible to station only a few mechanical pumps at intervals around the machine and otherwise provide no "forevac" pumps. These will then be turned off when ionic pumping starts. It is desirable that this mechanical pump not contaminate the system. Such a pump exists in the Roots mechanical pump which uses counter-rotating figure-eight shaped rotors machined to close tolerance so that no oil seal is necessary. The Roots pump has been used successfully at Brookhaven at pressures as low as 10^{-4} mm.

In order to "rough" the CS vacuum system from atmospheric to 30 microns in one hour, one will need about 12 Roots pumps stationed around the 5 mile circumference. The smallest size Roots pump, 86 cfm., will be adequate, since the aperture of the vacuum system limits the pumping speed (already at a pressure of about 40 mm.). Starting from atmospheric pressure, a single Roots pump connected to 50 sections on each side will reduce the average pressure to 40 mm. in about 2 minutes. The time to reach 30 microns, limited by the conductance of the long tube, is of the order of one hour.

The combination of Roots mechanical pump (with its auxiliary roughing pump), ion pumps, and an all-metal vacuum system seems especially attractive for a small-aperture system of great length. The all-metal system keeps outgassing low, small fail-safe pumps are compatible with remote tunnel location, and the non-contaminating features of both ion- and Roots- pumps promises to maintain a clean system.

VII Cost

(A) Extrapolation from Brookhaven AGS Cost Experience

An estimate of probable cost of the vacuum system, including development, fabrication, installation, and tests can be obtained by using Brookhaven figures[2)] for their AGS machine. Table IV summarizes

AGS experience:

TABLE IV

BROOKHAVEN AGS VACUUM SYSTEM COSTS[3)]

	Overall	No. Units	Cost/Unit
Pumping and controls	$350,000	48	$7300
Chambers, flanges, etc.	400,000	240	1665
Design and test	100,000	--	--

The cost of the Evaporion pumps was $3000 each (without controls); controls were made separately to Brookhaven specifications. Brookhaven was the first user of Evaporion pumps and worked with Consolidated Vacuum Corporation to develop the final pump.

The new discharge-type ion pumps are in some ways simpler (no motor-driven wire feed mechanism) than the Evaporion pump. The Cambridge Accelerator will use the discharge ion pump. Several competitive ion pumps are now on the market. The CEC 30-lps "DriVac" unit, complete with power supply, magnet, and local controls costs $1630 for a single unit; unit cost will be lower if ordered in quantity.

The Roots pump in the 86 cfm. size costs $1800 list.

Power distribution, monitoring, and remote controls are related to other control functions and cost is difficult to estimate at this stage. Since units are "fail-safe", elaborate interlocks and quick-acting valves are unnecessary. However, a monitoring system to indicate a region of high pressure will certainly be needed. We arbitrarily assign $1000/pumping station for such auxiliary control-indicators.

The construction of the AGS vacuum chamber at Brookhaven involved a number of designs and tests (ribbed units, etc.). The Cascade Synchrotron will benefit in many ways by AGS experience. On the other hand, the new ideas of integral pole-tip-and-vacuum-chamber will undoubtedly require design, development, and test. Hence, we assign an equal amount, $100,000, to "design and test".

Actual construction of chambers, flanges, etc., would be done on mass production basis, including tests "on-site" in contractor's plant. It is felt that Brookhaven's unit costs (per 10 foot vacuum section) are indicative of our unit costs (per 27 foot section), since most of the labor is in the section ends. Since some gain in efficiency may be expected in building 1200 units (instead of 240), we adopt a construction cost of $1500 per section.

The resulting estimated costs are given in Table V for Case I (3 second storage) and Case II (1 second acceleration).

TABLE V

ESTIMATED CS MAIN RING VACUUM SYSTEM COSTS

Case I: 400 ion-pumps, 12 mech. pumps
Case II: 120 ion-pumps, 12 mech. pumps

	Unit Cost	$\$10^3$ Case I	$\$10^3$ Case II
Pumping and Controls			
Ion-pumps, complete	$1500	$ 600	$ 48
Mechanical pumps	1800	22	22
Remote control indicators	1000	400	132
		$1022	$ 202
Chambers, flanges, etc. (1200 vacuum sections)	1500	1800	1800
Design and test		100	100
ESTIMATED TOTAL COST (MAIN RING)		$2922	$2102

The Main Ring vacuum costs are therefore $2 or $3 million, respectively, for straight-acceleration or storage modes of operation of the Main Ring.

Booster Ring vacuum system costs for 1 cps and 10 cps operation have already been estimated[7)] to be $0.7 million and $1.0 million. (The vacuum system of the CS Booster Ring has the same aperture but only half

7) See CTSL-12, "Preliminary Cost Estimate for a 300 Gev Cascade Synchrotron", M. H. Blewett (see p. 4).

the length of the Brookhaven AGS which cost $0.85 million.)

Thus, for both CS Rings the total vacuum systems cost may be estimated as $2.8 or $4.0 million.

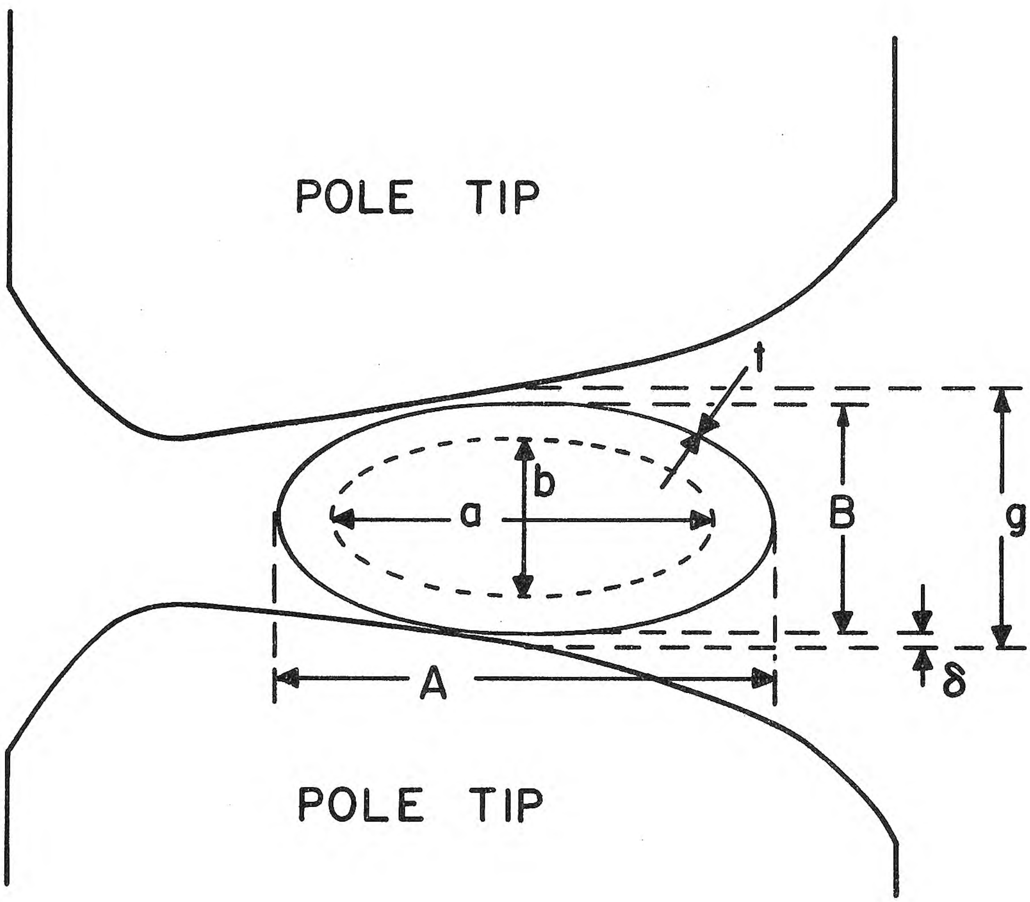
(B) Comparison with Previous Preliminary Estimates

Although all present estimates are preliminary (pending thorough engineering study), a brief comment may be made as to why the Main Ring cost estimate is lower than that of Sands (CTSL-10) or Blewett (CTSL-12) which were $4 million and $6 million respectively.

The principal reasons are the use of smaller pumps, the assumption of vacuum chamber costs on the basis of sections rather than length, and some assumed savings in unit costs due to mass orders.

VIII Conclusions

A thin-wall (.034" Inconel) all-metal vacuum system for the Main Ring is proposed. Despite low conductance, pressures $\sim 10^{-6}$ mm. Hg can be obtained with 400 small discharge-type ion pumps. This low pressure is required if 3-second "storage" of 10 Gev protons is planned; otherwise, 10^{-5} mm. Hg seems practical (using 120 pumps). Eddy current effects in such a small, thin-wall chamber are very small. The cost estimate (for Main Ring and Booster vacuum systems) is $3-4 million.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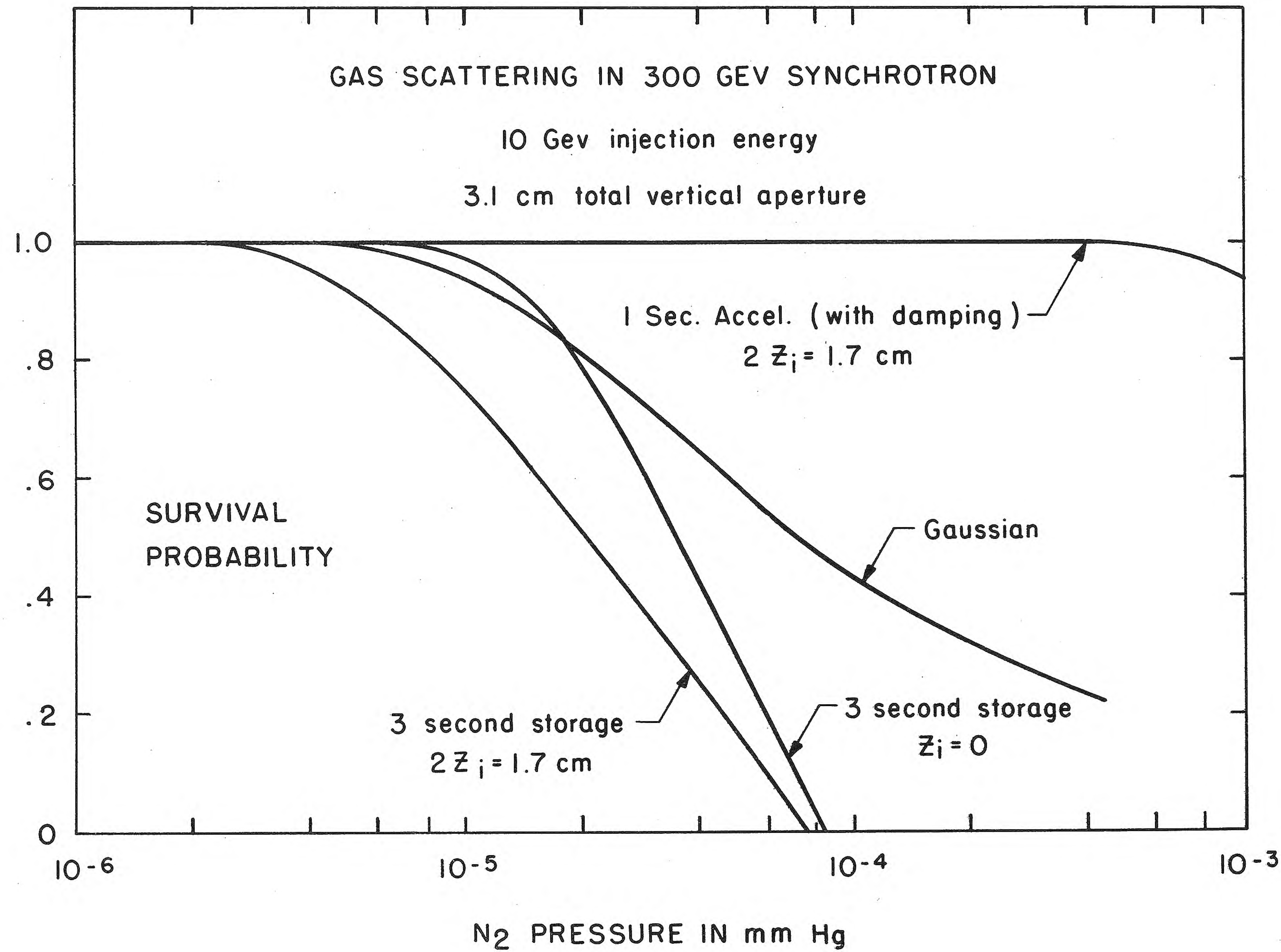
GAS SCATTERING IN 300 GEV SYNCHROTRON
10 Gev injection energy
3.1 cm total vertical aperture
1.0
.8
.6
.4
.2
0
SURVIVAL PROBABILITY
1 Sec. Accel. (with damping)
$2 Z_i = 1.7$ cm
Gaussian
3 second storage
$2 Z_i = 1.7$ cm
3 second storage
$Z_i = 0$
10^{-6}
10^{-5}
10^{-4}
10^{-3}
N_2 PRESSURE IN mm Hg