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ACCELERATOR DEPARTMENT
Informal Report

200-GeV ISA WITH ROOM TEMPERATURE MAGNETS

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ABSTRACT

A conceptual design study of 200-GeV proton intersecting storage accelerators with room temperature magnets is presented. The key to this study was the desire to keep the electric power consumption to an acceptable level (40 MW). The design has been optimized by choosing small-gap (4 cm) aluminum coil dipoles operating at about 15 kG. The luminosity of this machine is limited to about 10^{32} cm^{-2}sec^{-1} by transverse space-charge effects. An order of magnitude higher luminosities can be obtained by adding a booster of modest cost. A novel vacuum system using distributed Ti-sublimation pumps results in considerable savings. A cost comparison with a high-luminosity superconducting machine is given.

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I. Assumptions and Basic Design

In this report, we present the conclusions from a conceptual design study of a 200-GeV ISA with room temperature magnets. A similar study was previously carried out by Courant,[1] who established a list of parameters for a machine of the same energy and a total circumference of $4.25 \times C_{AGS} = 3430$ m requiring 20-kG warm magnets. However, he did not include a cost estimate for his particular design. In the Gray Book,[2] a comparative cost estimate for a warm ISA was based on NAL-type magnets operating at 15 or 20 kG. It was assumed that the injection system, experimental insertions, tunnel cross-section, cost of vacuum system per unit length, construction schedule, and manpower be identical for the ISA with superconducting or room temperature magnets. Under these assumptions, it was concluded that a saving in capital cost of about 20% and order of magnitude smaller operating costs would result from using superconducting magnets.

The motivation for a new comparative study was given by our intuition that magnets designed for the NAL accelerator may not be economical in the operation of storage rings. In carrying out this exercise, we have avoided considering the feasibility of large superconducting magnet systems. Since, furthermore, our cost estimates are based on the same general assumptions entering the ISABELLE study, the present report may be useful in a general comparison of room temperature vs superconducting machines, but should <u>not</u> be taken as an absolute point of reference. With more effort, the cost of the conventional solution could have been determined quite accurately; as it stands, however, the cost estimates quoted are not more accurate than those for the superconducting solution which contains figures with some uncertainties.

The key to our study was the desire to keep the electrical power consumption to an acceptable level. Because of the current attitudes toward energy usage, and the uncertainty of its future cost, we have chosen an

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[1] E.D. Courant, BNL Accelerator Dept. Report CRISP 72-4 (1972).

[2] J.P. Blewett and H. Hahn, ed., ISABELLE Preliminary Design Study, BNL Report 16716 (1972).

arbitrary limit of 40 MW in the dipoles (about 50 MW total) probably a smaller power consumption than would result from the conventional optimization of operating and capital costs. This limit was chosen such that it would not cause a marked increase in the power consumption of the Laboratory. It should be emphasized that this is the power at full energy. Many colliding beam experiments like to obtain excitation functions of the reactions being studied, so that the average power is less than the maximum by a duty factor proportional to the root mean square energy, which we take as 0.6. Furthermore, we believe that a moderately intensive program of exploitation, allowing timing for experimental access, machine studies, and beam stacking and acceleration, would provide about 3000 hours per year of colliding beam time. This power limitation then implies an annual energy consumption of about 90 GWh, a quantity indeed not very significant on the Brookhaven scale.

The magnet has been designed using aluminum conductor, which seems to offer substantial savings for this type of magnet. As shown in a subsequent section, the total capital costs are optimized by selecting a magnetic field of about 15 kG. Keeping the experimental insertions unchanged, this choice leads to a total circumference of $6 \times C_{AGS} = 4843$ m.

As expected, we found that economical operation requires magnets with small gap; here, $2g = 4$ cm was chosen. It turns out that the small magnet gap and concomitant small vacuum chamber aperture together with the large circumference imposes severe performance limitations viz. space charge and transverse resistive wall effects. To obtain luminosities comparable to the superconducting machine, it is considered necessary to rely on a 200-GeV booster. The third ring would be located in the same tunnel and, as shown below, adds only a reasonable fraction to the total cost.

Associated with the magnet design is a novel type of vacuum system which results in a major saving compared to the conventional approach without compromise in performance. The essential point of this vacuum system is the use of a continuously distributed titanium-sublimation pump as integral part of the aluminum vacuum chamber.

We have considered alternatives which span a large range of performance and cost. Since we concluded that substantial savings are only possible at the expense of reduced energy or luminosity, we focused our attention on two options for a 200-GeV colliding beam facility: the principal difference being the injection energy which is 30 and 200 GeV in Options I and II respectively, implying the provision of a 200-GeV booster accelerator in Option II.

The principal parameters of each option are listed in Table I. The circumference of the machine is fixed at 6 × C_{AGS}. The design assumes fourfold symmetry with four experimental insertions, each 250 m long; the momentum matching sections are part of the insertions. Four injection and ejection insertions, each 100 m long, have been assumed. The lattice cell structure adopted here uses separated function magnets with a FODO sequence.

TABLE I. Parameters of Warm ISA

	Option I	(IB*)	Option II
Final energy, GeV	200		200
Injection energy, GeV	28.5		200
Circumference (6 × C_{AGS}), m	4843		4843
Current, A	1	(0.36)	10
Luminosity (200 GeV), $cm^{-2}sec^{-1}$	1×10^{32}	(8×10^{31})	1.5×10^{33}
Number of dipoles/ring			
- regular lattice, m	408 × 6.15		400 × 6.27
- insertions, m	48 × 6.15		48 × 6.27
Magnet half gap, cm	2		2
Vacuum chamber half aperture, cm	1.5		1.5
Lattice parameters:			
ν-value	≈ 20		≈ 60
Number of regular cells	4 × 17		4 × 50
Length unit cell, m	50.6		17.2
Length exp. insertions, m	4 × 250		4 × 250
Maximum β, m	86		29
Crossing point β_o, m	2		2
Beam height at injection, cm	1.0	(2.4)	0.4
Beam width at injection, cm	1.6	(2.5)	0.5

*Option IB assumes bunched beams during operation.

- In Option I, the regular lattice structure is subdivided into $4 \times 17 = 68$ unit cells, each $L = 50.6$ m long and containing six 6.15-m dipoles and two 3-m quadrupoles. With this, a reasonable ν-value of about 20 can be obtained allowing injection above the transition energy. The resultant betatron phase shift per cell is about $\pi/2$ and the maximum β-value is, in the thin lens approximation, $\beta_{max} \cong 86$ m.

- In Option II, the regular lattice structure is subdivided into $4 \times 50 = 200$ unit cells, each $L = 17.2$ m long and containing two 6.27-m dipoles and two 1-m quadrupoles. Since we are not constrained here by the correct choice of transition energy, a higher ν-value may be adopted. A ν-value of about 60 is now obtained, again with a betatron phase shift per cell of $\pi/2$ and $\beta_{max} = 33$ m. The booster would have the same lattice as in Option I, but the magnet design would be more economical by reducing the conductor cross section (since power consumption is here not a design consideration).

At first we consider beam transfer from the AGS to the ISA based on stacking in the longitudinal phase space of the ISA (energy stacking scheme[3]). The emittance of the AGS at transfer is[4] $\epsilon_V = 0.3\ \pi$ μrad·m, resulting in a maximum rms beam height in the ISA of $\sigma_V = 2.5$ mm rms in Option I. The vacuum chamber with its clear aperture of $2h = 30$ mm is adequate but shaving to reduce the vertical beam size may be indicated. The emittance after acceleration in the booster is estimated to be $\epsilon_V = 0.04\ \pi$ μrad·m leading to a maximum rms beam height of $\sigma_V = 1$ mm rms. The vacuum chamber height in Option II is adequate.

The total horizontal beam width corresponding to a momentum spread of $\Delta p/p = 0.3$ and 0.4 % which is required to obtain the nominal operating current of 1 and 10 A, is at injection $2a \cong 1.6$ cm and 0.5 cm in Options I and II, respectively. Consequently, it is not practical to achieve wide ribbon beams as would be desirable for space charge reasons.[5]

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[3] E. Keil and A. Sessler, BNL Accelerator Dept. Report CRISP 72-74 (1972).

[4] The AGS emittance is dependent on the number N_{AGS} (in units of 10^{12}) of protons accelerated in the AGS according to $\epsilon \cong N_{AGS} \times 0.25\ \pi\ 10^{-6}$ m·rad.

[5] M. Month and K. Jellett, BNL Accelerator Dept. Report CRISP 73-4 (1973); M. Month and R.L. Gluckstern, BNL Accelerator Dept. Report AADD 73-8 (1973).

We have assumed in the above discussion that the beams are unbunched for physics experiments. A bunched mode operation is conceivable in which each ring of Option I is filled with six AGS pulses retaining the original bunch structure through acceleration and experiments. In this mode of operation (IB) no advantage is gained from using a separate booster. The simplicity of this approach, although it entails some difficulties in regard to counting rates in a certain class of experiments, leads us to adopt it as the principal mode of operation. The limit on the injected current is here set by the vertical aperture. We estimate that 0.36 A can be achieved, corresponding to an AGS pulse with 6 × 10^{12} protons.

II. Current Limitations and Estimated Luminosities

The "ultimate" current limit in a single ring is imposed by the incoherent ν-shift resulting from the transverse space charge effects which, at higher energies, are predominantly due to image forces caused by the surrounding vacuum chamber and magnet poles. Neglecting a possible neutralization of the beam, one can write the expressions for the vertical ν-shift of a circulating beam with a total of N particles per ring and with dimensions small compared to the vertical semiapertures of the vacuum chamber h and magnet gap g in the form[6]

$$\Delta\nu_{inc} \cong - \frac{NRr_p}{\pi\gamma\nu} \left\{ \left(1 + \frac{1}{B\gamma^2} \right) \frac{\epsilon_1}{h^2} + \frac{\rho}{R} \frac{\epsilon_2}{g^2} \right\}$$

with the classical proton radius $r_p = \mu_o e^2/4\pi m_p = 1.535 \times 10^{-18}$ m, the bunching factor B equal to the ratio of average to maximum current, the storage ring radius $R = C/2\pi$, the bending radius ρ, and the geometrical constants ϵ_1 and ϵ_2. For the parallel plate geometry assumed here, the geometrical constants are known to be[6] $\epsilon_1 = \pi^2/48$ and $\epsilon_2 = \pi^2/24$. For $N = 3.6 \times 10^{13}$ (that is six AGS pulses with 6 × 10^{12} protons or 0.36 A circulating current) one obtains a $\Delta\nu \cong 19/\gamma\nu$. At injection this leads to a tune shift of 0.03 in Option I and 1.5 × 10^{-3} in Option II.

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[6] L.J. Laslett, Proc. Summer Study on Storage Rings, Accelerators, and Experimentation at Super-High Energies, Brookhaven 1963, p. 324.
L.J. Laslett and L. Resegotti, Proc. 6th Int. Conf. High Energy Accelerators, Cambridge, Mass. 1967, p. 150.

Assuming a tolerable ν-shift on the order of 0.1 (the CERN ISR operates with[7] $\Delta\nu_v \cong 0.05$ at 20 A) we find the upper limit of

$$I \cong 1.2 \text{ A in Option I}$$

and

$$I \cong 24 \text{ A in Option II .}$$

We must conclude that due to the small magnet gap and large circumference the maximum current of 10 A of the superconducting counterpart can only be achieved in Option II.

An estimate for the threshold current imposed by the transverse resistive wall instability is obtained by scaling the CERN ISR current according to[8]

$$\frac{I}{I_{ISR}} = \left(\frac{h}{h_{ISR}}\right)^3 \frac{\gamma\nu}{\gamma_{ISR}\nu_{ISR}} \left(\frac{R_{ISR}}{R}\right)^{5/2} \left(\frac{\rho_{ISR}}{\rho}\right)^{1/2} \frac{f(a/h)_{ISR}}{f(a/h)}$$

with the ratios of

- chamber height, $h/h_{ISR} = 1.5/2.5$ cm
- machine radius, $R_{ISR}/R = 150/770$ m
- chamber resistivity (stainless steel vs Al) $\rho_{ISR}/\rho = 10^{-4}/2.5 \times 10^{-6}$ $\Omega\cdot$cm
- form factor[9] $f(a/h)_{ISR}/f(a/h) \approx 0.7/0.9$ in Option I, $\approx 0.7/1$ in Option II
- energy $\gamma/\gamma_{ISR} = 31/29$ in Option I, 214/29 in Option II
- betatron number $\nu/\nu_{ISR} = 20/9$ in Option I, 60/9 in Option II.

Taking $I_{ISR} \approx 20$ A we find the limits

$$I = 0.85 \text{ A in Option I, and}$$

$$I = 15 \text{ A in Option II .}$$

We note that the resistive wall instability, too, presents a severe limit on the current achievable in the ISA. But it has been demonstrated on many accelerators that coherent oscillations of the beam can be damped out by the use of electronic feedback.[10] In conclusion, we assume a current of I = 1 and 10 A as operational current in Options I and II, respectively.

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[7] B. Autin, J.P. Gourber, H. Laeger, and L. Thorndahl, IEEE Trans. NS-20, No. 3, 802 (1973).

[8] M. Month, BNL Accelerator Dept. Report CRISP 73-7 (1973).

[9] L.J. Laslett, V.K. Neil, and A.M. Sessler, Rev. Sci. Instr. 36, 436 (1965).

[10] L. Thorndahl and A. Vaughan, IEEE Trans. NS-20, No. 3, 807 (1973).

To avoid the brickwall effect[11] it will be necessary to prestress the working line as done at the CERN ISR[7] and to provide sextupole and octupole correction magnets.

The expected luminosities are calculated by scaling the results for the superconducting ISA without changing the geometry and optical properties of the experimental insertions. Obviously, Option II would provide a larger luminosity than $L \simeq 1 \times 10^{33}$ of the superconducting version. The scaling laws for estimating the luminosity are based on the simple model[2] of a collinear collision region of adjustable length ℓ and uniform charge density in the beam. In this model, the luminosity is given by

$$L = \frac{\pi}{\langle\varepsilon\rangle} \frac{I^2}{c\, e^2} \operatorname{arctg} \frac{\ell}{2\beta_o}$$

with the average emittance $\langle\varepsilon\rangle = \sqrt{\varepsilon_h \varepsilon_v}$, the amplitude function at the center of the collision region β_o, and the other quantities as previously defined. The beam-beam interaction will limit the maximum luminosity obtainable. A measure for this basically nonlinear effect is the linear tune shift

$$\Delta\nu = \frac{r_p}{ec} \frac{\pi I}{\langle\varepsilon\rangle \gamma} \ell$$

which in the case of proton-proton storage rings is thought to be limited to $\Delta\nu_{max} \approx 5 \times 10^{-3}$. Taking into account the beam-beam limit, the luminosity may be expressed as

$$L = \frac{\pi I}{\langle\varepsilon\rangle\gamma} \frac{I\gamma}{ce^2} \operatorname{arctg} \left(\frac{1}{2} \frac{\langle\varepsilon\rangle\gamma}{\pi I} \frac{ec}{r_p \beta_o} \Delta\nu_{max} \right) .$$

For a given injector the phase space density and thus the ratio $\pi I/\langle\varepsilon\rangle\gamma$ can be kept constant by an optimum beam transfer or beam shaving. Consequently, the luminosity scales with the current rather than with the square of the current. In practice arctg may be substituted by its argument, leading to[12]

$$L_{max} \simeq \frac{1}{2} \frac{I\gamma}{e r_p \beta_o} \Delta\nu_{max} .$$

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[11] M. Month, BNL Accelerator Dept. Report CRISP 73-17 (1973).

[12] A more accurate formula for round Gaussian beams is given by E. Keil, Report CERN/ISR-TH/73-48. The small difference can be neglected in the context of the present discussion.

We find the numerical relation at 200 GeV of

$$L/I \cong 1 \times 10^{32}\ \mathrm{cm}^{-2}\mathrm{sec}^{-1}/\mathrm{A}$$

with the current I in amperes, resulting in $L = 10^{33}$ for the Option II, and about $10^{32}\ \mathrm{cm}^{-2}\mathrm{sec}^{-1}$ for Option I.

The luminosity in the bunched beam mode (Option IB) is estimated from[13]

$$L_o = f\ n_B\ \frac{N_B^2}{\langle\varepsilon\rangle\beta_o}$$

with f the revolution frequency, n_B the number of bunches, and N_B the number of protons per bunch. To be valid it is required that the total bunch length $\ell < 2\beta_o$. The beam-beam interaction imposes a limit on the number of protons per bunch

$$N_{Bmax} = \frac{\gamma\langle\varepsilon\rangle}{r_p}\,\Delta\nu_{max}\quad .$$

In our case where the maximum $\gamma\langle\varepsilon\rangle = 46\ \pi\ \mu\mathrm{m}\cdot\mathrm{rad}$ is imposed by the vacuum chamber aperture one has $N_{Bmax} \approx 5 \times 10^{11}$ which, incidentally, is independent of γ since $\gamma\langle\varepsilon\rangle$ is invariant. $N_{Bmax} \approx 5 \times 10^{11}$ corresponds to an AGS pulse with 6×10^{12} particles. The maximum luminosity follows to be

$$L_o = \gamma\ \frac{f\ n_B N_B}{r_p \beta_o}\ \Delta\nu_{max}$$

which gives at 200 GeV the value $L = 8 \times 10^{31}\ \mathrm{cm}^{-2}\mathrm{sec}^{-1}$. In principle, the luminosity could be increased by a larger number of bunches. This, however, would reduce the distance between bunches C/n_B (67 m for $n_B = 72$ as taken here) and seriously complicate the geometry of the experimental insertion.

We therefore assume that the operation with bunched beams, which is straightforward and desirable from the point of view of the machine design, would be the normal operating mode in the option without booster.

Finally it should be mentioned that it is impractical to increase the gap sufficiently to raise the current limit imposed by the incoherent tune shift to values comparable to the superconducting ISA. From the above

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[13] C. Pellegrini, Annual Review of Nuclear Science, Vol. 22 (1972), p. 1. See also L. Smith, PEP Note-20, giving $L = L_o\,\{x^{3/2}\,[1 - \mathrm{erf}(x)]\,\exp x^2\}$ with $x = \beta_o/\sigma_\ell = 4\beta_o/\ell$. For $\ell = 2\beta_o$ one has $L = 0.91\ L_o$.

formulas follows that a circular cross section of the beam tube ($\epsilon_1 = 0$) and a gap of about 10 cm would be required. A magnet design which keeps the power consumption at the 40 MW level is prohibitively expensive. Minimizing capital equipment cost plus operating expenses over 10 years can in principle be done but it is not obvious that this would lead to an economical solution.

III. Magnet System

The cost of the magnet system depends strongly on the choice of the magnetic field in the dipoles. However, the total cost of magnet system, tunnel, and vacuum system is only weakly dependent on the magnetic field. We costed two different solutions with circumference of $C = 7\ C_{AGS}$ ($B \approx 13$ kG) and $C = 6\ C_{AGS}$ ($B \approx 15$ kG), and found a cost ratio of 1.06:1.0, indicating that the cost considerations provide no decisive arguments. Collective effects clearly favor the machine with smallest circumference whereas the field quality of the magnet indicates lower magnetic fields. The choice of a machine with $6 \times C_{AGS}$ and $B = 15$ kG appears to be a reasonable compromise.

The magnet design is based on the use of Al instead of the more usual Cu coils. At an assumed cost of \$5.50/lb for Cu and \$4.00/lb for Al the total costs for camel-back-type Cu and Al coils stand in a ratio of 3:1 whereas the cost of iron cores (\$0.35/lb) is essentially the same. As an overall result we find that the use of Al allows for a substantial savings. A further cost reduction is achieved by the use of flat coils (\$3.00/lb) instead of camel-back-type coils. In summary, we find a unit cost (6-m length) of

19.1 k\$ with Al flat coil,
20.0 k\$ with Al camel-back coil,
34.4 k\$ with Cu camel-back coil .

The schematic cross section of the magnet chosen is shown in Fig. 1. The magnetic properties of this design have been computed indicating that

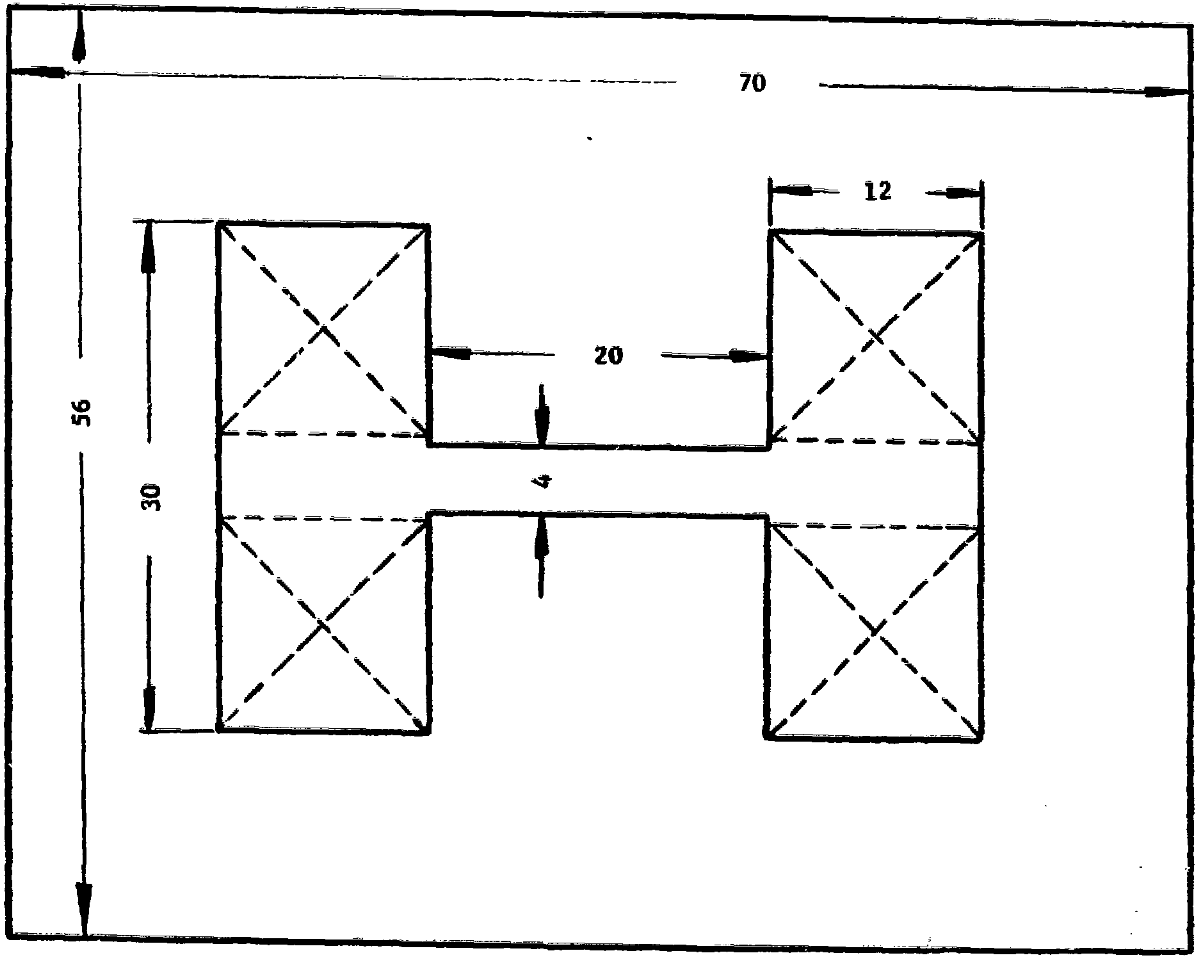

Fig. 1. **Cross section of warm magnet (dimensions in centimeters)**

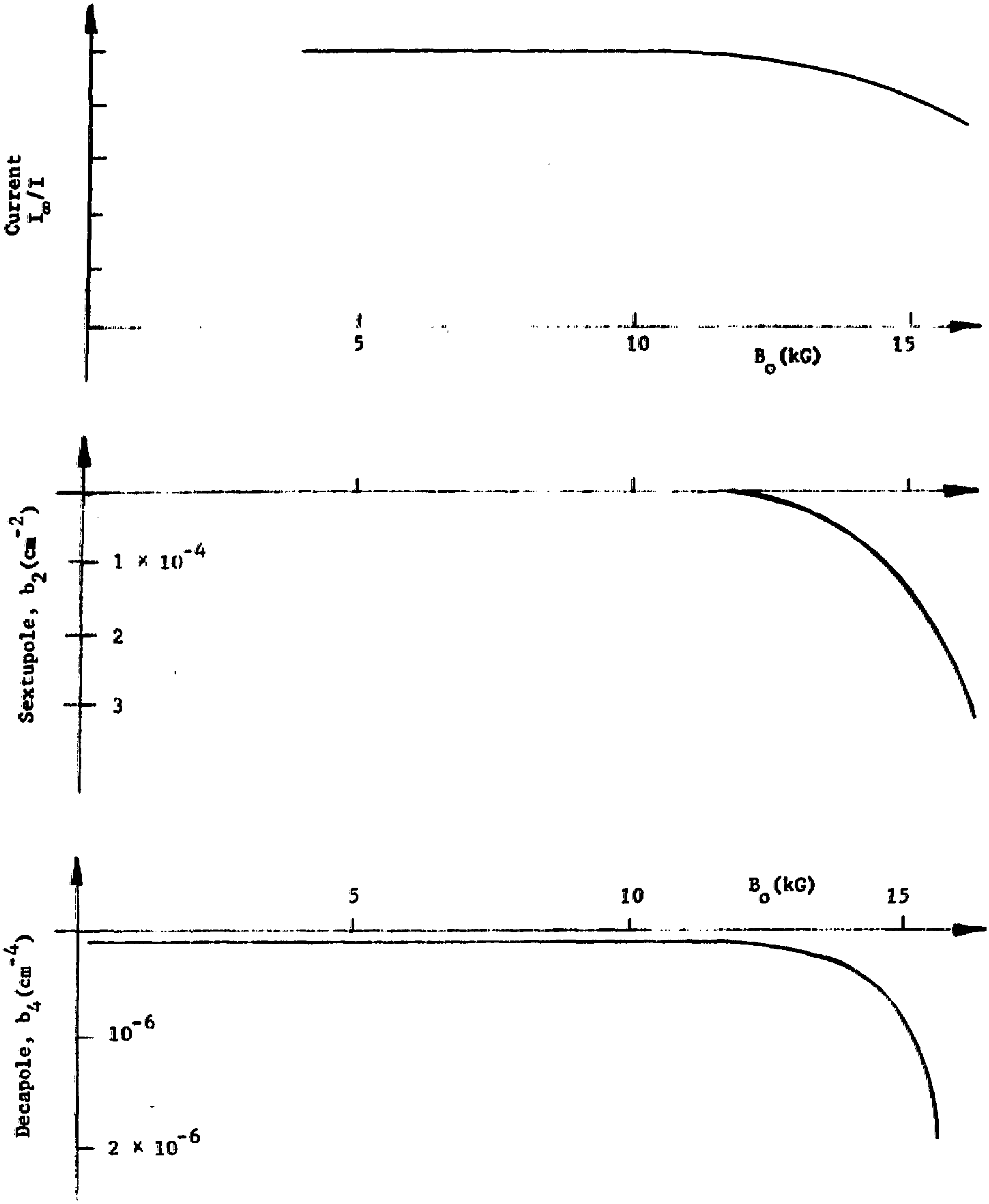

Fig. 2 Computer results for warm magnet shown in Fig. 1. The coefficients are defined by writing the magnetic field in the median plane as $B(x) = B_o(1 + b_2x^2 + b_4x^4)$.

its field quality is adequate up to 15 kG (Fig. 2). The stored energy per magnet is about 60 kJ at 15 kG and thus 27 MJ per ring.

IV. Vacuum System

In this section, a summary of the vacuum system for the warm ISA will be given. A more detailed discussion may be found in Ref. 14. The magnet gap severely limits the vacuum chamber height (3 cm). Adequate pumping speed must be obtained by an increased chamber width which is only limited by the width of the magnet pole ($\approx$ 20 cm).

The conductance of an elliptical duct with 3 cm x 20 cm internal dimensions is about 30 liter/sec which may be compared to the 60 liter/sec of the CERN ISR beam tube. Using the results of Refs. 14 and 15, we conclude that the pressure bump instability limits the current to $\eta\, I_{cr} \approx 6$ A since the H-type magnet considered prevents the distance between pumps to be shorter than the magnet length ($\approx$ 6 m). From the CERN experience on the typical desorption coefficients $\eta \leq 2$, we conclude that such a vacuum system would permit currents of about 3 A, which is adequate for Option I but not for Option II.

Another approach using distributed pumping appears to circumvent this problem and is suggested to be used in the present design. SPEAR[16] employs distributed sputter-ion pumps for a vacuum in the 10^{-8} to 10^{-9} Torr range. The magnetic field is provided by the ring magnets. Besides the rather complicated structure and the requirement of high voltage, the pumping speed of these pumps decreases by a factor of 2 to 3 in the 10^{-11} Torr range, making them less suitable for our design. Distributed titanium sublimation, pumps, on the other hand, present a possibility of an inexpensive vacuum system with ample pumping to the 10^{-11} Torr range all along the chamber and permits large circulating currents. The possible cross section of the proposed aluminum chamber shown in Fig. 3 uses a Ti-Mo rod located in the larger of

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14. H.J. Halama, BNL Accelerator Dept. Report AADD 73-7 (1973).

15. E. Fischer and K. Zankel, Report CERN-ISR-VA/73-52 (1973); O. Gröbner and R.S. Calder, IEEE Trans. Nucl. Sci. NS-20, No. 3, 760 (1973).

16. J. Rees et al., Proc. 8th Int. Conf. High Energy Accelerators, Geneva 1971, p. 145.

the side ducts. The smaller channel is used for heating during bake-out and can also provide cooling in a future conversion into an electron storage ring.

During the bake-out, the chamber will be pumped by 150 liter/sec sputter-ion pumps between the magnets (6 m apart). After the bake-out, a maximum pressure of 2×10^{-9} Torr occurs in the middle of the magnet if an outgassing rate of 10^{-12} Torr liter/sec cm^2 and the gas conductance for N_2 are assumed. In fact, the pressure will be lower since most of the residual gas will be H_2. When the Ti rod is heated and Ti deposited on the walls the pressure will drop to the 10^{-11} Torr range. The resulting pumping speed S_0 per 1 cm length of the chamber shown in Fig. 3 is given in Table II.

TABLE II. Pumping Speed Per Centimeter of Chamber Length Due to the Ti-Mo Rod.

Gas	H_2	N_2	O_2	CO	CO_2	H_2O	CH_4	A	He
S_o (liters/sec)	30	45	90	90	90	30	0	0	0
S_{eff} (liters/sec)	12	4	4	4	3	5	0	0	0

Since we want to prevent the deposition of Ti on the areas to be bombarded by ionized residual gas molecules, we limit the aperture to 4 mm (Fig. 3) which decreases the pumping speed to S_{eff} in Table II. Ti-Mo rods similar to those commonly used in sublimation cartriges yield a total of over 0.1 g of Ti per centimeter of length which provides 1.8 Torr-liter of pumping. A monolayer of Ti can be deposited either at preset intervals or whenever the pressure increases above the 10^{-11} Torr range. This represents at least two weeks if an outgassing rate of 10^{-12} Torr liters/sec cm^2 is assumed. Non-getterable gases will be pumped by sputter-ion pumps between the magnets. Under normal conditions, the rods should last indefinitely, but even if a new Ti film of a few monolayers had to be deposited every day, the rods would last about 10 years.

It is clear from the above discussion, that the proposed chamber combined with Ti pumping can provide a very economical and effective vacuum system. Thus our cost estimate of 7.2 M$ is about equal to the 7.8 M$ spent on a

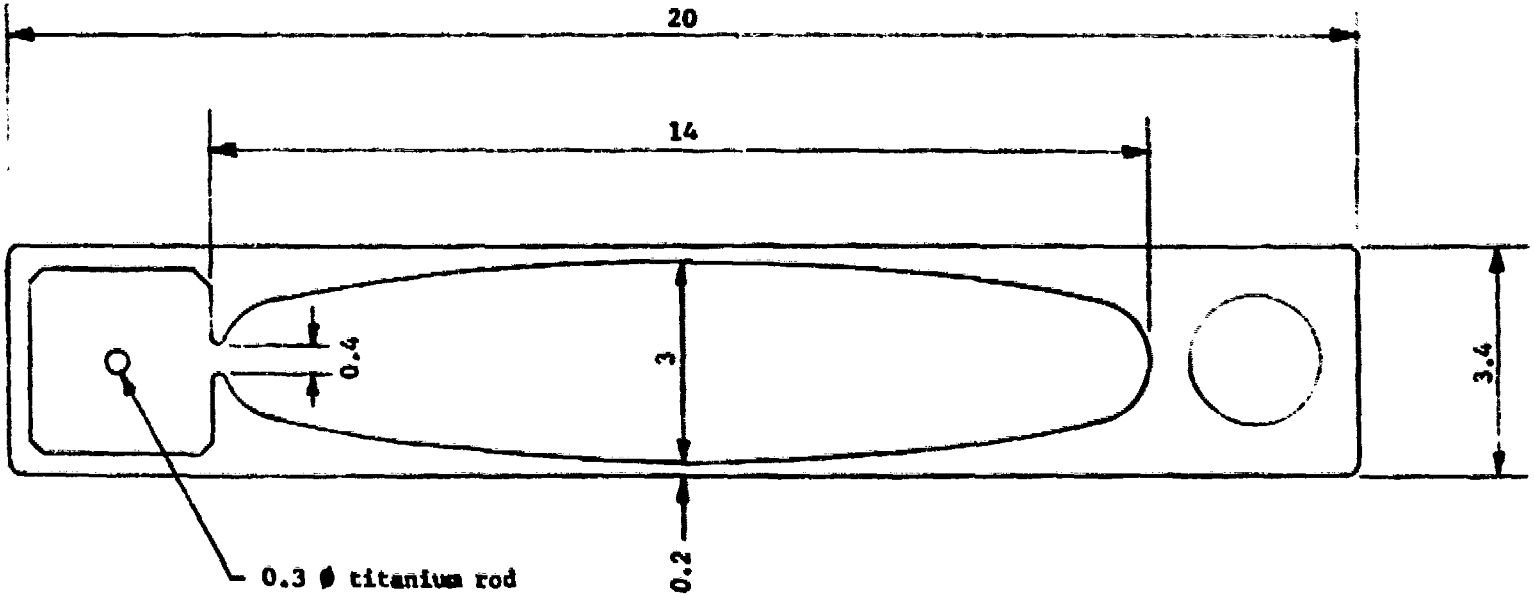

Fig. 3. Cross section of vacuum chamber (dimensions in centimeters)

smaller vacuum system at CERN.[17] The main features resulting in the cost savings are:

- The UHV pumping is obtained through the use of Ti sublimation directly inside the vacuum chamber.
- An aluminum chamber is much cheaper, easier to machine, and requires lower bake-out temperature than stainless steel.
- The sections of the vacuum chamber are welded together wherever feasible rather than flanged.

In the final design of the vacuum system a number of other problems will have to be considered, among which are:

- Induced eddy currents in the vacuum chamber during acceleration.
- Heat generation in the vacuum chamber in the case of bunched beams.
- Effect of a bunched beam on the pressure bump phenomenon.

However, in first order, no significant changes in the general conclusions reached here are expected.

V. Comparative Cost Estimate

We have carried out a rough cost estimate for Option IB and Option II of a 200-GeV ISA, the results of which are summarized in Table III. Since there exists no detailed technical design we resorted frequently to a simple scaling from other machines, in particular the cost estimates given in the design reports for the CERN ISR,[17] the NAL 200/400-GeV accelerator (NAL),[18] and the NAL 100-GeV pp colliding beam storage rings (NALSR).[19]

The cost estimate for the superconducting 200-GeV ISABELLE has been redone since the last edition of the "Gray Book".[2] The values quoted do not yet represent the official final numbers. However, few significant changes are expected. In fact, the ISABELLE estimates are probably more accurate than those given here for the ISA with conventional magnets in spite of the

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[17] K. Johnsen, CERN Report AR/Int.SG/64-9 (1964).

[18] R.R. Wilson, E.L. Goldwasser, and F.T. Cole, eds., NAL Design Report, 2nd ed., 1968.

[19] R.R. Wilson, L.C. Teng, eds., Proton-Proton Colliding Beam Storage Rings for the National Accelerator Laboratory, Design Study, 1968.

TABLE III. ISA Cost Estimates in M$ (without escalation)

	Superconducting ISABELLE*	200-GeV ISA with Warm Magnets	
		Option IB	Option II
TECHNICAL COMPONENTS			
Magnet system	35.2	27.2	38.9
- Dipoles			
Magnet power supply	0.7	9.3	9.7
- LCW cooling			
Refrigeration	12.5	0	
Vacuum system	5.9	7.2	9.0
RF system	3.7	0.8	2.2
Beam transfer	2.3	2.3	6.3
Modification AGS	0	0	0
Computer and controls	1.7	1.7	2.4
Miscellaneous	0.6	0	0
Component cost	62.6	48.5	68.5
EDIA (25%)	15.3	12.1	17.1
CONVENTIONAL FACILITIES			
Ring tunnel	4.4 } 20.8	8.3 } 24.8	26.0
Experimental halls, etc.	16.4 }	16 }	
AEM (20%)	4.2	5.0	5.2
Subtotals	102.9	90.4	116.8
CONTINGENCIES			
Technical components (25%)	} 23.4	15.2	21.4
Conventional facilities (15%)	}	4.5	4.7
Total	126.4	110.1	142.9

*Cost estimates are subject to change.

uncertainties of a new technology. The estimates for Option II are without doubt the least accurate.

Our cost figures for technical components quoted in Table III include fabrication and installation. EDIA (engineering, design, inspection and administration) costs on technical components are taken to be 25% of component costs. AEM (architectural engineering and management) costs on facilities have been estimated at 20% of facilities costs.

Contingencies on technical components have been estimated at 25% of total component cost whereas contingencies on conventional facilities have been estimated at 15% of total facility costs.

The superconducting ISABELLE cost estimate has been obtained by a different procedure, but an attempt was made in Table III to allow for a direct comparison of subtotals.

To arrive at our cost estimate the following additional assumptions were made:

Option IB

Magnet system. The fabrication cost of the dipole magnets has been estimated directly, $2 \times 456 \times 19.1 \times 10^3 = 17.4$ M$. The total cost (including quadrupoles, other magnets, installation and magnet alignment) is obtained by using the multiplier of 1.56 taken from NALSR.

Ring magnet power supply and cooling. The assumed power handling capabilities for bending magnets alone is about 40 MVA, the total requirement is taken to be 50 MVA, which is estimated at 5 M$. Using a typical multiplier 1.3, we obtain the total cost of 6.5 M$. Low conductivity water cooling is estimated directly from NAL to be 2.8 M$. The total for power supplies and cooling is thus 9.3.

Vacuum system. The cost of the vacuum system was estimated directly at 7.2 M$. The use of distributed Ti-sublimation pumps represents a major cost saving factor.

Rf system. The bunched beam operation in Option IB requires a peak voltage of 50 kV. No rigorous requirements on the impedance are known in this case, and we take roughly 1/10 of the AGS value, that is 10 kΩ. Thus one needs 250 kW per ring, estimated at a sum of 500 k$. The cost of the total rf system is taken as 700 k$ plus 100 k$ for a low level rf system with feedback capabilities.

Beam transfer. The cost for beam transfer, injection, and protective ejection equipment in Option IB does not differ substantially from ISABELLE. The transfer tunnel is somewhat longer which has been taken into account in the conventional facilities cost.

Computer and controls. We take the cost of the computer and control system to be equal to ISABELLE.

Conventional facilities. It is assumed that ring tunnel costs are twice those of ISABELLE, with the costs for four experimental halls unchanged. Adjustments are made for the absence of refrigerator and compressor housing and increase of electric power handling capabilities.

Option II

Magnet system. The increment for the booster is obtained by multiplying the dipole cost of 8.7 M$ with the NAL multiplier 1.34.

Ring magnet power supply and cooling. The power handling capability of the booster is 3 MVA, assuming an acceleration time of 10 sec. The estimated incremental cost is 1.3 × 0.3 = 0.4 M$. Provision for additional cooling capacity does not seem required.

Vacuum system. The increment for vacuum of the booster, which need not be UHV, has been estimated directly as 1.8 M$. Equipment shared with the ISA is the main reason for this comparatively low figure.

Rf system. The ISA rf system is here similar to the ISR stacking system ($h = 72$) with a peak voltage of about 25 kV and a low impedance ($< 100\ \Omega$) obtained by feedback. We therefore take the ISR value of 1 M$. The booster rf ($h = 72$) requires 280 kV with an impedance of 70 kΩ corresponding to about 1.1 MW. The booster rf is estimated at 1.4 M$ and the total in Option II is 2.2 M$.

Beam transfer. Beam transfer, injection, beam dump in the booster is essentially identical to the ISABELLE and taken as 2.0 M$. Transfer at 200 GeV from booster to ISA is in addition and represents a major fraction of the total cost in this option. In the NALSR study 4.3 M$ was allotted for this purpose. Therefore we here estimate a total of 6.3 M$.

Conventional facilities. It is assumed that the cross section of the main tunnel must be increased to accommodate all three rings (10 M$). We would expect, however, that the booster would be added at a later time, then in a separate tunnel.

VI. Summary

Although no detailed design of a Warm Intersecting Storage Accelerator was carried out, the information collected in the foregoing study contains sufficient detail to permit an informed comparison with the superconducting ISABELLE solution, both in regard to technical performance and construction cost. Out of this study results the important conclusion that an ISA with conventional magnets is technically and economically feasible.

The main limitation of the conventional solution is the small magnet gap with a concomitant large incoherent ν-shift due to transverse space charge effects. This limit is, however, of little or no concern in the case of bunched beam operation and the luminosity is here limited by beam-beam effects to roughly 10^{32} cm^{-2}sec^{-1}. Storage of bunched proton beams is admittedly an untried innovation, but the bunching factor required in our design is very conservative when compared to other serious proposals. It also should be pointed out that our conclusions do not depend on the bunched-beam scheme. As a matter of fact, a slightly higher luminosity is obtainable with unbunched beams. The design luminosity of the superconducting ISABELLE is given as 1.0×10^{33} cm^{-2} sec^{-1}. We have shown that an equal or higher luminosity can be achieved with a conventional machine by using a booster accelerator.