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Informal Report

INTERIM LOW COST 100 GeV ISA

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Abstract

A design study of an interim low cost 100 GeV p-p ISA is presented. It is conceived as a first stage toward the ultimate goal of a high energy (200-300 GeV) superconducting phase. The guiding principle has been compatibility with the transition to the final superconducting stage. The first phase performance goals are to achieve an average luminosity of 10^{32} cm^{-2}sec^{-1} at a top proton energy of 100 GeV. The primary constraints on the design effort have been to keep down the cost and the electric power consumption. These constraints lead to the choice of small gap (4 cm) aluminum coil dipoles operating at 15.3 kG. However, the beams will be brought together for collision with superconducting magnets in the intersection regions. For this purpose, the experimental insertion dipoles designed for the superconducting ISA can be used. The resultant design cost estimate is $69.2 M, while the total electric power consumption is estimated to be 25 MW. The option of storing electrons is considered, providing an e^-p luminosity of $\sim 10^{32}$ cm^{-2}sec^{-1}.

INTERIM LOW COST 100 GeV ISA

1. Basic Design

We present a design study of an interim low cost 100 GeV ISA. It is conceived as a 1st stage toward the ultimate goal of a high energy (200 - 300 GeV) superconducting phase.(1) This guiding principle has led us to choose tunnel, magnet arrangement, injection system , dump system, and vacuum system in the 1st stage so as to be compatible with the transition to the superconducting phase. This has meant a somewhat higher cost in the 100 GeV phase than would have been the case if a design optimization had been performed without thought to phase II. But the savings in the transition to the final stage certainly justifies this procedure.

The performance goals are to achieve an average luminosity of 10^{32} $cm^{-2}sec^{-1}$ at a top energy of 100 GeV.

The primary constraints on the design effort has been to keep down the cost and the power consumption. These constraints lead to the choice of small gap (4 cm) aluminum coil dipoles operating at 15.3 kG identical to those in the 200 GeV room temperature option described in Ref. (2). However, the beams will be brought together for collision with superconducting magnets in the intersection regions. For this purpose, we can use the experimental insertion dipoles designed for the superconducting ISA. The resultant design cost estimate is $69.2 M, while the dipole magnet power consumption is estimated to be 20 MW. Operating at 13 kG, i.e. at an energy of 85.4 GeV, the power consumption is reduced to 12 MW.

To satisfy our guiding principle of minimizing cost in the transition to phase II, we choose the beam transfer, injection (including injection rf system), vacuum and dump systems to be identical to those in the superconducting ISA design except for the fact that fewer vacuum pumps will be needed in view of the lower current. This is reflected in our cost estimate which is detailed in a later section. The accelerating rf system, however, can be operated at a significantly lower voltage, meaning a substantial decrease in rf power. Since the cost of the rf system is directly related to the rf power, a large saving relative to the full cost is made in stage I.

In section 2, we consider the influence of using room temperature magnets on the lattice structure. A list of required magnets is given. The performance of our 100 GeV design and concomitant limitations are discussed in section 3. Specifically, the luminosity is limited by how much current can be stacked in each ring and how low the value of β at the crossing point, β^*, can be made. We assume that the luminosity is beam-beam limited and we take for the weak-strong beam-beam tune shift limit the currently accepted value of 5×10^{-3} for protons. Vacuum considerations and transverse space-charge effects limit the attainable beam current. We find for the maximum current, 3.5 A. To achieve a luminosity of 10^{32} $cm^{-2}sec^{-1}$, β^* will have to be reduced to 5.0 m. The question of how the low β relates to the chromaticity together with the question of how the low current implies low momentum spread which in turn influences the rf cost and power consumption will be treated in more detail in the section on performance. In section 4, we present some details on the potential use of these rings for electron storage and, thereby, e^--p collisions. Finally, in section 5 can be found a detailed cost estimate.

A list of the main parameters, in particular those significantly different from the stage II superconducting design, is provided in Table I.

TABLE I: Main Parameters for Interim 100 GeV ISA

Final Energy, GeV	100.5	
Injection Energy (kinetic), GeV	28.5	
Average Radius (3-1/3 x R_{AGS}), m	428.2	
Average Current, A	3.5	
Dipole Magnet half-gap, cm	2.0	
Vacuum chamber half-height, cm	1.5	
Tune	19.4	
Length, normal cell, m	30.2	(no. = 40)
Length,[*] multipurpose insertion, m	50	(no. = 4)
Length,[*] experimental insertion, m	200	(no. = 4)
Magnet filling factor in curved portions of rings	0.815	
Beam Height[†] (total) at inj., cm	0.9	
Beam Width[†] (total) at inj., cm	1.7	
Horizontal aperture for stacking at inj., cm	4.1	
Emittance (h and v) at inj., rad·m	$0.4\pi \times 10^{-6}$	
Momentum spread (total) at inj.	3.5×10^{-3}	
V_{rf} (accelerating system, peak), kV	10	
rf Power,[‡] MW	0.2	
Dipole Power consumption,[‡] MW	20.0	
Total Electric power consumption,[‡] MW	25.0	

β^* (m)	Total Experimental free space (m)	Luminosity ($cm^{-2} sec^{-1}$)
5	20.8	1.1×10^{32}
10	50.0	0.55×10^{32}

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[*] Only straight portion.

[†] At maximum β in normal cell. ($\beta = 52.0$ m, $X_p = 2.3$ m for horizontal case)

[‡] Both rings.

2. Lattice

Our fundamental presumption in this 100 GeV design study is the fact that it is the first stage of a two-stage process to achieve an anergy 200-300 GeV with superconducting magnets. To allow a simple transition, we design the 100 GeV machine to fit into the tunnel for the superconducting ISA. We retain therefore the identical octant structure. Each octant has a length 1/8 of the ISA circumference. If we subtract the "straight" lengths for experimentation, injection and ejection, we are left with the "curved" or bending portion of the octant, amounting to 211.3 m. Thus, with a 62% dipole filling, an energy of 201 GeV can be obtained with 40 kG magnets. If L_c is the length available for bending, B is the dipole field, and p the energy in units of magnetic rigidity (kg-m), then the filling factor required is

$$f = \frac{2\pi p}{BL_c} \quad .$$

With p = 3351.3 kG-m (100.5 GeV), $L_c = 8 \times 211.3$ m, B = 15.28 kG, the required filling is 81.5%. Assuming a minimum separation of 30 cm between magnets, this filling can be achieved with dipoles of length 6.15 m, leaving 1 m at each cell quadrupole for correcting magnets, consisting primarily of sextupole component for chromaticity correction.

The lattice structure is, in essence, identical to the superconducting ISA design. The magnets required are listed in TABLE II. For the purposes of a cost estimate, we have chosen to include superconducting magnets in the intersection regions for the purpose of bringing the beams into collision. If these magnets are the same as in the superconducting design, they serve our purpose for a 100 GeV machine and entail no incremental cost in the transition to the stage II full superconducting phase.

TABLE II: Magnet List

Component Name	Number (2 Rings)	Length (m)	Strength (for 100.5 GeV)	Comments
		(A) Room Temperature Elements		
B	448	6.15	15.3 kG	Main Dipole
QF	64	1.2	2.6 kG/cm	Cell Quad (HF)
QF	16	0.6	2.6 kG/cm	Cell Quad (HF)[*]
QD	80	1.2	2.6 kG/cm	Cell Quad (HD)
QI1	16	1.0	2.6 kG/cm	Multipurpose Insertion Quad (HF)
QI2	16	1.0	2.2 kG/cm	Multipurpose Insertion Quad (HD)
QI3	16	1.8	2.3 kG/cm	Multipurpose Insertion Quad (HD)
QI4	16	1.8	2.6 kG/cm	Multipurpose Insertion Quad (HF)
QE1	16	1.6	2.6 kG/cm	Experimental Insertion Quad (HF)
QE2	16	1.0	2.2 kG/cm	Experimental Insertion Quad (HD)
QE3	16	2.1	2.6 kG/cm	Experimental Insertion Quad (HF)
QE4	16	2.1	2.3 kG/cm	Experimental Insertion Quad (HD)
QE5	16	1.8	2.6 kG/cm	Experimental Insertion Quad (HD)
QE6	16	3.6	2.5 kG/cm	Experimental Insertion Quad (HF)
QE7	16	1.8	2.6 kG/cm	Experimental Insertion Quad (HD)
SX	160	0.5	0.035 kG/cm^2	Cell Sextupole
		(B) Superconducting Dipoles for Beam Collisions		
H1	16	1.53	20 kG[†]	SC Dipole (Horiz.)
H2	16	1.53	20 kG[†]	SC Dipole (Horiz.)
V1	16	5.03	20 kG[†]	SC Dipole (Vert.)
V2	8	5.03	20 kG[†]	Common to both beams
H3	8	1.93	20 kG[†]	Common to both beams
H4	8	2.44	20 kG[†]	Common to both beams

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[*] Half-Quads for service insertion matching.

[†] Designed for 40 kG.

3. Performance

The beam-beam limited luminosity for each collision region can be estimated from(1,3)

$$L = \left(\frac{I}{e} \right) \frac{\gamma \Delta\nu_v}{\sqrt{2}\, r_p\, \beta_v^*} \quad ,$$

where L is the average luminosity,
I is the average current in each ring,
γ is the energy in proton mass units,
$\Delta\nu_v$ is the vertical beam-beam tune shift,
β_v^* is the vertical β-value at the crossing point,

and we have assumed horizontal crossing. Since the energy is chosen, there are 3 parameters which determine the luminosity, $\Delta\nu_v$, I, and β_v^*.

Beam-Beam Limit and Crossing Angle

We take the beam-beam tune shift to be at the limit, $\Delta\nu_v = 5 \times 10^{-3}$. To attain this, we must choose a horizontal crossing angle, α, given by(1,3)

$$\alpha = \left(\frac{I}{e} \right) \frac{\sqrt{2}\, r_p\, \beta_v^*}{cb\gamma(\Delta\nu_v)} \quad ,$$

where α is the full crossing angle, and

b is the vertical beam half-size at the crossing point.

Anticipating a little, we have the maximum current, $I = 3.5$ A, and $\beta_v^* = 5.0$ m. Taking $\gamma = 107.1$ (100.5 GeV) and $b = 0.72$ mm(corresponding to an emittance, $\epsilon = 0.12\pi \times 10^{-6}$ rad·m at 100.5 GeV), we find for the crossing angle, $\alpha = 1.9$ mrad, and for the luminosity, $L = 1.1 \times 10^{32}$ cm^{-2}sec^{-1}.

Current Limit

The beam current is vacuum limited.(2) The critical current is determined by the conductance of the vacuum chamber, the pumping speed and the distance between pumps, the latter following essentially from the dipole length. Assuming as in the superconducting ISA design, a desorption coefficient, $\eta \approx 2$, and with a 14 cm x 3 cm vacuum chamber, we find for the vacuum limited current, 3.5 A.

The small magnet gap (4 cm) means the vacuum chamber will have a vertical half-height, h = 1.5 cm, in the curved (bending) portions of the lattice. This is small compared to the chamber radius of 4 cm in the cold ISA design. We must, therefore, examine the space charge limitations.(1,2) The beam is essentially unchanged from the latter design; thus, we need not consider the beam dominated effects. In fact, the reduction in current introduces a safety factor of about 3 as compared to the superconducting design. However, image effects, which are strongly dependent on h, must be looked into. Actually, it is important to point out that in the superconducting design, the current limitations from the resistive wall instability arise from the beam dependent term and not the image dependent term. It is thus not too surprising that stability from the resistive wall effect even with its strong dependence on h, can be achieved in the 100 GeV design with the reduced chamber height.

We must consider two effects, the standard resistive wall effect, which has an h^3 dependence, and the "brick-wall" effect, which arises as a consequence of the combined influence of the resistive wall effect and the incoherent image tune shift. The constraints due to these effects can be written as a lower limit on the tune spread, a sufficient amount of which is required to provide stabilization through Landau damping. The conditions are respectively(4)

$$\delta\nu > \frac{4\, r_p\, R^{5/2}\, I}{e\nu\gamma\, h_{eff}^3} \sqrt{\frac{2\varepsilon_o \rho}{c|k-\nu|}}$$

and

$$\delta\nu > \frac{0.7\pi^2\, r_p R^2 I}{12 e\, c\nu\gamma\, h_{eff}^2} \;,$$

where $\delta\nu$ is the full tune spread,

R is the average ring radius,

ν is the betatron tune,

h_{eff} is the effective (or average) vertical chamber half-height,

ρ is the chamber resistivity, in units of ohm-m,

ϵ_o is the free space dielectric constant ($\epsilon_o = 1/36\pi \times 10^{-9}$ sec/ohm-m),

k is the azimuthal mode number for the unstable mode ($k > \nu$).

Clearly, the constraint is most stringent at injection. Thus, taking $R = 428.2$ m, $\nu = 19.4$, $\gamma = 32$ (30 GeV), $\rho = 1.6 \times 10^{-8}$ ohm-m (aluminum), $k = 20$ (lowest mode), $I = 3.5$ A, and $h_{eff} = 2.4$ cm (assuming 64% of the circumference requires the small chamber height of 3 cm, while 36% of the circumference, in the experimental and multipurpose straight sections, can have a chamber with radius 4 cm), we obtain

$$\delta\nu > 2.36 \times 10^{-3} \text{ (classical resistive wall),}$$

and $$\delta\nu > 0.033 \text{ (brick-wall).}$$

It therefore appears that 3.5 A could be achieved without either working line prestressing or electronic feedback. Some of either or both could however be added if necessary in practice.

The lower current of 3.5 A allows us to stack with lower total momentum spread.(5) Suppose we reduce the momentum spread by a factor of 2 from the superconducting ISA design to $\Delta p/p = 3.5 \times 10^{-3}$. Now, we have that the voltage required for rebunching and acceleration is related to $\Delta p/p$ by

$$V \propto (\Delta p/p)^2 \quad ;$$

while for the limiting coupling impedance to the beam we have

$$|Z_s| \propto \frac{1}{I} (\Delta p/p)^2 \quad ;$$

and for the rf power,

$$P_{rf} \propto V^2/|Z_s| \sim I(\Delta p/p)^2 \quad .$$

Thus, the required voltage is reduced by 4 to V_{rf}(peak) = 10 kV (for a harmonic number, h = 2). The coupling impedance also must be reduced, but by a factor of only 1.4 to 0.5 kΩ. And finally, and most importantly, the rf power is reduced by a factor of 11.4. This means a relatively insignificant rf power requirement of 100 kW for each ring. This substantial power saving, and its associated cost reduction, certainly justifies the redesign of the accelerating rf system.

Low β Limitation

The limitation to the reduction of β^* arises from the large β-values at the nearest focusing elements. Since horizontal crossing implies that only the vertical β^* be low, the maximum β is related to β^* by

$$\beta_{max}\,\beta^* \approx \ell^2,$$

where ℓ is the distance from the crossing point to the first vertically focusing quadrupole. Our crossing arrangement requires a space of 25 m for bending magnets on either side of the crossing point. This large length is self-imposed in the sense that we have chosen to use the magnets designed for the 200 GeV stage II in order to save the cost of replacing them in the transition. To obtain $\beta^* = 5$ m, and setting a limit $\beta_{max} = 250$ m, we have $\ell = 35.4$ m, which means a free space for experiments of $2\ell_{exp} = 20.8$ m around the crossing point. A much larger free space for experiments can be obtained if we increase β^* to 10 m. With the same limit on β_{max}, we have $2\ell_{exp} = 50$ m. The choice $\beta_{max} = 250$ m is rather conservative compared to the cold ISA design. It incidentally relaxes the tolerance on quadrupole placement. But, more significantly, it means the chromaticity is kept to manageable size. It should be recognized that chromaticity correction and control is to be done with separate sextupole magnets and not with coils in the dipoles as in the cold ISA design. In our case, therefore, large chromaticity means "more" length for sextupoles, which, in turn, means less length for bending, which ultimately translates to more magnet power consumption (higherdipole field) or less energy, i.e. a reduction in performance. The choice β_{max} = 250 m gives a chromaticity, or rate of tune change with momentum of $\nu' = p\, d\nu/dp \approx -40$. To correct this chromaticity in both vertical and horizontal planes requires sextupoles at all cell quadrupoles. For sextupoles of length 0.5 m, we estimate a required peak sextupole strength 0.035 kG/cm^2.

Luminosity

As already mentioned, $\beta^* = 5$ m gives a luminosity $L = 1.1 \times 10^{32}$ cm^{-2}sec^{-1}. Because of the chromaticity limitation, this means that the total experimental free space available is 20.8 m. Allowing the value of β^* to increase to 10 m has the effect of reducing the luminosity to $L = 0.55 \times 10^{32}$ cm^{-2} sec^{-1}, while increasing the available experimental free space to 50.0 m.

4. Electron Experiments

We consider the possibility of accelerating electrons up to 15 GeV in one of the proton rings and colliding them with 100 GeV protons stored in the other ring. This would require the addition of an rf system$^{(6)}$ with power capability of about 6 MW. The vacuum chamber of the ring used for storing electrons would have to be cooled to avoid excessive temperature rise from absorption of synchrotron radiation. Preacceleration in an electron linac followed by acceleration to 4 GeV in the AGS would be done.$^{(1)}$ Assuming the same interaction horizontal crossing geometry as for p-p collisions at 100 GeV (α_H = 1.9 mrad, β^* = 5 m) and an electron beam current of 200 mA, one gets the following luminosity and tune shifts for 15 GeV e$^-$ 100 GeV p collisions:

$$L_{e^- - p} = 0.8 \times 10^{31} \text{ cm}^{-2}\text{sec}^{-1}$$

$$\Delta\nu_p^y = 1.1 \times 10^{-4}$$

$$\Delta\nu_e^y = 0.06$$

For lower electron energies, higher electron currents can be stored for a given rf power, resulting in higher luminosities. The electron current can be increased as E_e^{-4} until $E_e = 7.9$ GeV, at which point $L_{e^- -p} = 1.0 \times 10^{32}$ $\mathrm{cm}^{-2}\mathrm{sec}^{-1}$, $\Delta\nu_p^y = 0.005$ and $\Delta\nu_e^y = 0.106$. Although the electron tune shift is on the high side through the electron energy range 7.9 GeV $\leq E_e \leq$ 15 GeV, it can be reduced, if necessary, by going to lower β-values at the intersection point in the electron ring. Also, increased vacuum requirements arising as a result of the synchrotron radiation impinging on the vacuum chamber could necessitate a change from discrete to distributed pumping.(2) If discrete pumping is to be used in Stage II, for economic reasons pertaining to magnet size, this means a total cost increase in the amount of the cost of the distributed pump system, about $3 M. However, because distributed pumping is comparatively lower in cost, a Stage I saving of the order of $1 M would actually result.

5. Cost Estimate

We have performed a cost estimate for the interim 100-GeV storage accelerators. The details are presented in Table III. In arriving at the listed values, we have followed the usual procedure. Technical components 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 facility 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.

With regard to technical components, we have assumed the injection system, the vacuum system and the central control system to be identical to the ISA superconducting design.(1) The ring room temperature magnets are individually costed. This includes dipoles, quadrupoles and sextupoles. The power supply cost for these magnets is listed. We also give a separate listing for the superconducting magnets to be used in the collision areas and include as well the associated refrigerator cost. As we have already pointed out, the rf accelerating system cost represents a substantial saving as compared to the cold ISA design. This is reflected in the cost summary in Table III. In the area of facilities, we have attempted some cost savings. Again, here, the constraint of minimizing cost in the transition to Phase II has been self-imposed. The main Stage I saving is the assembly buildings. We choose to construct one of the four assembly buildings in Stage I, deferring the remaining three buildings to Stage II. We finally arrive at a Stage I cost estimate of $69.2 M, as detailed in Table III. The incremental cost to Stage II is estimated at $79.6 M, leading to a final cost of $148.8 M. This is an increase in total cost due to the use of the 2-phase approach of $22.3 M over the ISABELLE cost.(1) Of this amount, about $15 M (Note that the remaining $7 M is EDIA and contingency cost) represents the cost of the room temperature magnet system with associated power supply and cooling, which is a "salvageable" commodity. For example, these magnets could be used in the future construction of separate electron rings, such an addition markedly enhancing the facilities available for physics in the ISA complex.

TABLE III: Cost Estimate: 2-Stage ISA ($M)

	Stage I	Stage II Increment	Total Stage II
Accelerator Systems			
I. Injection System	2.28	0	
II. Main Magnet System	10.35	33.03	
III. Magnet Power Supply & Cooling	4.50	0	
IV. Special Superconducting Magnets (+ dewars)	2.01	0	
V. Refrigeration System	3.00	9.91	
VI. Vacuum System	3.91	1.95	
VII. RF System	1.11	2.62	
VIII. Central Control System	1.73	0	
IX. Correction Coil System	0	0.51	
Accelerator Systems Total	28.89	48.02	76.91
Facilities			
I. Land Improvements	0.84	0	
II. Magnet Enclosure	4.43	0	
III. Beam Injection Tunnel	0.79	0	
IV. Research Halls - Large (3)	4.55	0	
V. Research Halls - Small (1)	0.69	0	
VI. Compressor House	0.97	0	
VII. Refrigerator Houses (2 - 2)	0.57	0.57	
VIII. Assembly Buildings (1 - 3)	0.70	2.70	
IX. Central Control & Service Bldg.	1.60	0	
X. Yard Tray, Piping & Gas Storage Yard	0.30	0	
XI. Utilities	1.87	0	
Facilities Total	17.31	3.27	20.58
AEM (@ 20%)	3.46	0.65	4.11
EDIA (@ 25%)	7.22	12.00	19.22
Subtotals	56.88	63.94	120.82
Contingency - Facilities @ 15% Acc. Systems & EDIA @ 25% A/E @ 20%	12.31	15.63	27.94
Totals	69.19	79.57	148.76

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