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10/5/78

10.575

BNL 50804

UC-28

(Particle Accelerators and
High-Voltage Machines - TID 4500)

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ISABELLE, ACCUMULATORS, BUNCHED BEAMS AND COSMICTRONS*

M. Month

December 5, 1977

* Transcript of Accelerator Department Seminar, 12/8/77.

ACCELERATOR DEPARTMENT

BROOKHAVEN NATIONAL LABORATORY
ASSOCIATED UNIVERSITIES, INC.

UPTON, NEW YORK 11973

under contract No. EY-76-C-02-0016 with the

UNITED STATES DEPARTMENT OF ENERGY

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PRINTED IN THE UNITED STATES OF AMERICA
Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

Price: Printed Copy \$ 4.50 ; Microfiche \$3.00

ABSTRACT

An elaboration of the ISABELLE concept as the model for a high energy, high luminosity proton-proton facility is given. Its place in the total high energy physics program is discussed. Certain features of the ISABELLE design which have not been consolidated, in particular injection and modes of beam operation, are considered. A new scheme is reviewed, one which could provide quick beam turn-on after construction, one in which there is a high probability of reaching and perhaps even exceeding the design objectives, one which should provide comparatively more flexible and reliable operation for physics, and finally one whose presence opens up a window to a much higher energy region. The new system involves the use of a physically separate current accumulator, allowing, therefore, the optimal utilization of the superconducting structures. The fact that an obvious addition to the complex will permit pp collisions in the 4 TeV center-of-mass energy region, which corresponds to an equivalent lab energy of $\sim 10^{16}$ eV, i.e. cosmic ray energies, prompts the added structure to be referred to as the COSMICTRON. The facility operated in the "new" manner proposed is considered to be "the best ISABELLE that can be built."

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I. Introduction

The general structure of a high energy, high luminosity proton-proton facility is rather well defined as a result of the extensive study over the past few years. ISABELLE is, in fact, the conceptual culmination of this work and is undoubtedly a realistic foundation upon which a detailed and specific design can be formulated. With funding of the ISABELLE Project close to realization, it is no doubt time to finalize the design.

Qualitatively, we expect ISABELLE to provide:

1. High energy collisions.
2. High luminosity.
3. High operational reliability.
4. Sufficient space around the collision region for experimental setup.
5. The flexibility to operate in different modes with respect to both energy and luminosity.
6. Quick turn-on and production of physics at the earliest time, with the given constraints on cost and funding profile. And perhaps -
7. The opening of a window to the future with ISABELLE acting as an injector for the production of colliding proton beams at even higher energy.

Thus, a highly concentrated period of study is needed in the next few months so that a final detailed design will exist when the ISABELLE construction phase gets underway.

In our work over the last few years at BNL, we have considered many variations on the basic ISABELLE concepts. We have, for example, contrasted a superconducting versus a conventional magnet ISABELLE. We have looked into the possibility of short bunch collisions at zero crossing angle. We have even given thought to the possible advantage of a fast cycling booster in order to operate in the ISR manner. However, most of the ideas generated proved fruitless and the basic ISABELLE conceptual design remained unaltered except for some technical improvements in magnet construction techniques and in the cryogenics area.

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On the other hand, we have also discovered that there are certain aspects of ISABELLE as it is presently proposed which cause us to question whether we can readily attain our design objectives, or, in fact, to question whether these objectives can be reached at all. In any case, it is clear that the operation of ISABELLE as it now stands will be very difficult. Consequently, any change which would simplify operation is indeed welcome.

With this in mind, we set out in late 1975 to develop an ISABELLE scheme which we feel confident will turn-on rapidly and quickly achieve the performance claimed. I believe we have succeeded in this effort. Therefore, allow me to present to you a qualitative picture of what might be called "the best ISABELLE that can be built."

This talk can be divided into three sections. First, I will review where ISABELLE stands with respect to the total high energy physics program. Second, I will review the basic framework upon which a detailed ISABELLE will, without doubt, conform. And finally, I will present a picture of what we at present consider to be "the best ISABELLE that can be built."

II. ISABELLE's Place in High Energy Physics

The history of accelerators has essentially been a demand for bigger and so costlier machines. From the first, each new machine has produced physics which raised more questions than it answered and demanded even larger accelerators. It is the familiar philosophical paradox that the closer to the truth you appear to approach, the further away it, in fact, recedes. This process is sketched in Fig. 1. Listed are the rough costs, times when they appeared and gross sizes of some of the big proton machines. It appears that we are fast approaching an economic limitation which will prevent the process from continuing as it is.

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APPROXIMATE CIRCUMFERENCES OF SOME BIG ACCELERATORS

Fig. 1

As shown, there are three existing size (circumference) levels:

1. The 400 ft level - represented by the Cosmotron and Bevatron.
2. The $\frac{1}{2}$ -mile level - represented by the AGS and the ISR, and
3. The 2-3 mile level - represented by the existing Fermilab ring as well as the near future ISABELLE Project.

The fourth level is a projection into the perhaps 10-20 year future. It is undoubtedly fair to inquire what precisely this level should be. Is 30 miles the proper level to reach for? 20 miles? 10 miles? Perhaps, only 5 miles?

I will show you later that with the ISABELLE concept, possessing high energy, high current beams can lead to a rather reasonable "next size level" of 7-8 miles. It is not impossible that a rise in the level of magnet technology could mean that such a project might be constructed for not much more cost than the presently discussed

400 x 400 GeV ISABELLE machine. The question, of course, is, "Does the high energy physics community wish to move in the direction of higher energy proton-proton collisions?"

Now, size and energy are, without question, closely correlated. On the other hand, there is another dimension to take into consideration. Not all energy is of the same class. There are in reality two types of proton energy that we can speak of. If a single ring delivers protons to a fixed target, we talk of the accelerator or lab energy. This energy is quite different from the center-of-mass energy as shown in the energy-time graph of Fig. 2. It is important to recognize that in terms of available "new particle" energy, it is the center-of-mass energy that counts. Much of the lab energy is consumed as motion of the target so as to conserve momentum in the collision and so cannot serve as energy to produce "new mass".

Fig. 2. Interaction Energy in High Energy Physics Machines as a Function of Real Time

Once those points are appreciated, it becomes clear that a giant leap in "new particle" energy can be achieved by having 2 rings with proton beams circulating in opposite directions and periodically colliding. In this setup, the accelerator and center-of-mass energy become equivalent. This seems like a rather trivial and obvious solution now, but it should be remembered that the first p-p colliding beam machine, providing 52 GeV in center-of-mass energy, did not come into existence until 1970 in the form of the ISR. It can be noted from the energy-time graph that the Fermilab machine, which is a level above in size from the ISR (6.3 km in circumference compared to 1 km), can produce only about $\frac{1}{2}$ the center-of-mass energy of the ISR.

The boldness of the ISR builders, which today is capable of providing stable 25-30 A colliding beams for periods up to about 40 hours, has given us more than just the first p-p colliding beam facility. What may be even more important, it has also produced the great confidence necessary to conceive the more advanced ISABELLE Project, and probably in the near future it will lead to ISABELLE itself.

To be able to properly assess ISABELLE's place in high energy physics, consider how the appetite of particle physicists for "new mass" energy has grown over the last few decades. Observe also the phenomenal increase in energy from the ISR, the machine with the highest "new particle" energy existing today, to ISABELLE: from ~ 60 GeV to more than an order of magnitude higher, ~ 800 GeV. Note that a fixed target machine, to accomplish this, is "out of this world." Optimistically, 5000 miles in circumference is needed. Furthermore, because of the undoubtedly long time for protons to reach the required lab energy, the number of protons per unit time that can be attained would be exceedingly low. It may very well be that the only way to provide reasonable duty cycles for high energy fixed target machines is via beam spill from slow "storage accelerators", as is actually being proposed as the long term operating mode for the Fermilab doubler.

What may be even more significant than the absolute value of the obtainable center-of-mass energy in ISABELLE is the simple fact of life that at present there is no way other than through p-p colliding beams to come anywhere near such energies. Compare for example what energy

region is reasonable for proton-proton beams and electron-positron colliding beams. Electrons are even difficult to contemplate at somewhat modest center-of-mass energies. To reach 200 GeV in the center-of-mass requires an enormous amount of rf generator power (over 100 MW), and this power consumption level is achieved only by using low field bending magnets for the electron guide field so that the circumference required is more than 50 km. Thus, it is clear that the near future will not allow electrons to be used for center-of-mass energies even at the 200 GeV level. What has happened is that the sights of electron storage ring designers have lowered considerably from this level to about the 100-140 GeV center-of-mass region. But even to achieve 140 GeV in the center-of-mass still requires an rf power consumption of more than 100 MW and a circumference reduced from the 200 GeV case only by a factor of 2, to 25 km. On the other hand, for proton machines, ISABELLE, on the threshold of construction, will reach 800 GeV in the center-of-mass. Furthermore, as I have already intimated, ISABELLE's existence opens the door to a feasible next step. In particular, with an existing ISABELLE of 400 on 400, we can visualize a next size level of 5-8 miles capable of providing collisions with high luminosity and "new particle" energy in the range of 3-4 TeV! Note also that to reach these center-of-mass energies with a fixed target machine would require an accelerator energy in the cosmic ray region of about 10^{16} eV, implying roughly a machine circumference of about 80,000 miles!

III. The ISABELLE Concept

Quantitatively, the ISABELLE goals are:

- High energy collisions up to about 800 GeV in the center-of-mass.
- A high luminosity of about $10^{33} \text{ cm}^{-2} \text{ sec}^{-1}$ at top energy.
- A large range of available energies (over an order of magnitude), and
- A free space for experimental setup of about $\pm 30 \text{ m}$ (that is 60 m) around each collision point.

The main decision points have been

- High vs low beam current .
- Large vs small crossing angle .
- Strong vs modest focusing of the beam toward the collision point .

-- High vs low injection energy (equivalent to fast cycling booster vs slow stack acceleration)

-- Superconducting vs conventional magnets

The ISABELLE choices have been

-- Moderate current of about 8 A (aperture limitation is the dominant criterion for this choice)

-- Moderate crossing angle of about 14 mrad (a low beam-beam interaction for a given luminosity is one reason; another is that it gives sufficient natural beam separation at the first focusing quadrupoles 30 m from the collision points without the use of large aperture [> 30 cm] superconducting dipoles common to both beams.)

-- Modest focusing leading to β^* (vertical) at the collision points of about 5 m (this keeps the maximum β value down to under about 175 m)

-- "Low" injection energy combined with slow stack acceleration. (For a given longitudinal invariant beam density, the longitudinal impedance limit criterion favors "low" energy injection; in addition, injection with particle loss and beam scraping is better done at "low" energy when the magnets are operating at "low" field and are, therefore, not near their critical or quench temperature, meaning that there is a large temperature reserve for heat deposited in the coils by the "lost" protons.)

-- Superconducting magnets operating up to about 50 kG.

[A conventional magnet ISABELLE can produce only a low luminosity device, more than an order of magnitude less than with superconducting rings, the reason being that magnet power consumption would be unacceptably high (say > 100's MW) for a high current machine, that is one with a large magnet gap. A small gap design on the other hand implies unacceptably high image space charge fields to attain the required current for high luminosity.]

From these main decision choices, the general features of an ISABELLE design have emerged. To store high currents a large magnet aperture is needed (see Fig. 3). A reasonable choice is for a 12 cm

Fig. 3. ISABELLE Dipole Cross Section

coil i.d. The choice of a "warm" vacuum chamber dictates the need for insulation within the magnet aperture. Taking away space for helium channels and superinsulation, we are left with a vacuum chamber i.d. of 8 cm, which is quite adequate to store a 10 A beam without stimulating a vacuum pressure instability (the so-called pressure bump). However, the chamber aperture when filled with an 8 A beam is very tight and marginal at best during beam stacking, when there is very little space left for sagitta, residual orbit errors, scrapers, absorbers and the like (see Fig. 4). Finally, given magnets that can reach a field strength of 50 kG, and using our principle of simplicity in the design of the experimental insertions, we easily arrive at a tunnel magnet setup (Fig. 5) and $\frac{1}{2}$ -sextant magnet layout (see Fig. 6).

I.S.A. APERTURE SUBDIVISION AT A β_H MAX. LOCATION, 29.4 GeV

Fig. 4. ISABELLE Beam Aperture Utilization (No Current Accumulator)

Fig. 5. ISABELLE Magnet Enclosure Cross-Section

Fig. 6. ISABELLE $\frac{1}{2}$ -Sextant Magnet Layout

The major parameters for ISABELLE seem to have fallen into place like a well executed jigsaw puzzle solution, and we can conclude for ISABELLE:

- 1) High energy? The 400 GeV/beam should be attainable!
- 2) High luminosity? The 10^{33} should be attainable!
- 3) Free space for experiments? The ± 30 m should be sufficient! And -
- 4) It all fits on the BNL site! (see Fig. 7)

Given the ISABELLE conceptual design and the high probability of imminent funding, the concept must be transformed into a detailed final design. Thus, again we are confronted with decision points. These decision points are different from the types of choices that were required when developing the conceptual design. They can essentially be considered

within the context of two major aspects of ISABELLE and represent a new decision system confronting the ISABELLE decision makers:

- 1) Operation and performance - i.e. the present, and
- 2) Super-ISABELLE - i.e. the future.

Fig. 7. ISABELLE Ring Layout on BNL Site (No Current Accumulator)

Although there is a great deal of detail involved in analyzing the new decision system, there are at least two major areas of ISABELLE where the decision points must be faced boldly and without fear:

- 1) The area of injection and current accumulation, and
- 2) The nature of planned beam operation modes.

From our detailed study of the new decision system, we have found in fact, that these decision points can be reduced to two specific choices:

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1) A special current accumulator ring vs stacking into the main ISABELLE rings, and

2) Long bunch colliding beams vs unbunched coasting beam operation. These are the questions. Let me now try to provide the answers.

Seriously though, I want to suggest to you that if we are aiming for the "best ISABELLE that can be built" (from the point of view of operation, performance and super-ISABELLE) the choices should be:

- 1) A separate current accumulator ring, and
- 2) Colliding beams of "long" bunches (by "long" is meant bunches of the order of 100's of meters rather than just a few meters).

Let me attempt to put this talk into the larger perspective of the ISABELLE Project. The design has progressed to the point where the conceptualization of the basic systems, magnet, cryogenic, and vacuum, are essentially agreed upon. However, no consensus has been reached with regard to the system of operation, which includes the means of injection-ejection and the beam operating modes. An important implication perhaps worth mentioning here is that the needed decisions involve areas that do not require significant research and development effort. In fact, by and large, any changes from the existing ISABELLE proposal which are envisioned may not involve large deviations in cost. With these points in mind, I will now describe and discuss what we believe to be "the best ISABELLE that can be built."

IV. The Best ISABELLE That Can be Built

In this part of my talk I will discuss the total system that I submit is the "best" system. Now, this word "best" should be interpreted in a rather loose way. Since I will not present any absolute criteria for deciding the possible existence of anything better, I can't really prove in any logical manner that it is the "absolute best." However,

by contrasting this new system with the so-called ISR extrapolated system, I want to show:

- 1) That there is a better probability of obtaining colliding beams shortly after turn-on
- 2) That there is a much better probability that the design performance objectives will be reached
- 3) That the operation of the colliding beam facility will be more flexible and reliable, and
- 4) That with this new type of system, ISABELLE's existence opens up a window leading to future p-p colliding beams in a higher energy region.

The format I will use is to describe this "best" system and to detail its characteristics especially insofar as they relate to the four criteria I have just introduced. It might be interesting for you to consider the arguments I will present and attempt to decide in your own minds whether or not it is the "best" way for ISABELLE to proceed.

The basic idea for the new system is that the facility be composed of a sequence of physically separated functional steps. The different steps are sketched on the BNL site in Fig. 8.

Fig. 8. ISABELLE Ring Layout on BNL Site With Current Accumulator

The first step is a fast cycling device which will accelerate low current beam out of the low energy transverse space charge region. In other words we need an initial Energy Booster to fast accelerate beam. In the ISABELLE complex, this function is served by the AGS which fast accelerates (with a $\frac{1}{2}$ -second rise time) low current (~ 0.2 A average current) from 200 MeV kinetic energy to 30 GeV.

The second step is a ring of fixed or slow varying magnetic field which will function as an accumulator of current. The energy of this ring must be sufficiently high so that transverse space charge effects are avoided, but it should not be too high so that longitudinal (microwave) beam instabilities prevent high current stacks from being properly formed. A Current Accumulator operating at 30 GeV to stack current to about 10 A, to bunch the stack and possibly to accelerate the long bunch (i.e. the bunched stack) to the region of 40-60 GeV would be quite appropriate for the new ISABELLE system.

Step three consists of a pair of Superconducting Storage Accelerators. They will not only store the long high current bunches transferred from the accumulator but they will also be capable of slowly varying the energy of the high current bunches by an order of magnitude, thereby providing high luminosity p-p collisions over a wide energy range.

The fourth step involves the use of ISABELLE as a high current, high energy injector for a super-ISABELLE, what we have called a COSMICTRON. An example of a COSMICTRON selected to fit on the BNL site is shown in Fig. 9. With ISABELLE operating at a peak center-of-mass energy of 800 GeV, we can conceive of this super-ISABELLE providing high luminosity collisions in the center-of-mass energy range of roughly 1-4 TeV. This last step is really a proposal for a possible second stage ISABELLE in the event that the high energy community decides that p-p colliding beam physics in this energy region is the appropriate investment to make. This is one of the important points I want to emphasize here. With our new scheme

for ISABELLE, such a future possibility of studying interactions well into the cosmic ray domain, that is almost 10,000 TeV lab energy, becomes a realistic thought. In fact, extrapolating the energy-time graph of Fig. 2 indicates that technology could provide high energy physics with such a COSMICTRON by early 1990. It should, without doubt, be considered a serious competitor in high energy physics' future.

Fig. 9. BNL p-p Colliding Beam Complex Including 2 TeV X 2 TeV Cosmictron

Major Properties of the New System

The AGS injects low current pulses into the accumulator at 30 GeV. Some accumulator parameters are given in Table I. Its' circumference is taken to be that of the AGS. To achieve the ISABELLE performance, the accumulator should be capable of stacking about 20 A of current at a longitudinal density of 17 A/% momentum spread at injection. It should also be able to operate in the energy range 30-50 GeV. As an

example, I will use for calculating purposes a stack of 13.3 A, corresponding to a momentum spread of 0.55% at 50 GeV. Some of the gross stack parameters are given in Table II.

Table I: Accumulator Parameters

Circumference, C_{acc}	807 m (C_{AGS})
Injection Energy	30 GeV
Top Energy	50 GeV
Stack Density (30 GeV)	17 A/%
Stack Density (50 GeV)	24 A/% (20% dilution)

Table II: Properties of Stack in Accumulator

Current	13.3 A
Transfer Energy	50 GeV
Stack Momentum Spread	0.55 %
Bunched Stack Length	$5/6 C_{AGS}$
Bunch Momentum Spread	1.0 %

Once the stack is formed in the accumulator, any required shaving and cleanup as well as the rebunching of the stack is performed in the accumulator ring of conventional (room temperature) magnets. This avoids the necessity of performing these functions in a superconducting environment. The stack in the accumulator is bunched to a length $5/6 C_{AGS}$, corresponding to a momentum spread of 1%, in preparation for transfer at 50 GeV.

Accumulator bunches are injected into the superconducting rings by synchronous rf transfer. No beam manipulation other than that due to minor voltage adjustments is performed in these rings. In other words, the superconducting rings are required to handle only complete bunches injected directly into the center of the magnet aperture. Table III consists of some ISABELLE parameters pertinent to our discussion here.

Table III: ISABELLE Parameters

Circumference, C_{ISA}	4.04 km (5 C_{AGS})
Injection Energy	50 GeV
Top Energy	400 GeV
Top Field	50 kG
Average Current	8 A
Bunching Factor (Injection)	0.4
Peak Current (Injection)	20 A
Momentum Spread (Injection)	1 %
Beam Size at Injection (max, cell)	3.2 cm
Beam Size at Top Energy (max, cell)	5.5 mm

Three accumulator bunches are used to fill each superconducting ring, which is taken to have a circumference five times that of the AGS (4.04 km). The peak energy is 400 GeV corresponding to a peak magnetic field of 50 kG. The average current in each ISABELLE ring is 8 A. The maximum beam size in the ISABELLE 400 GeV lattice is about 3 cm at injection and shrinks to about $\frac{1}{2}$ cm at the top energy. The aperture utilization in this new scheme, shown in Fig. 10, should be contrasted with the significantly larger aperture utilization when no accumulator is used, as can be seen by comparing with Fig. 4.

Fig. 10. ISABELLE Beam Aperture Utilization With Current Accumulator

Let me emphasize a point: Within the superconducting environment, there is in the new scheme small aperture utilization and minimal beam manipulation. The implications, as compared to the case of no accumulator, are:

- 1) That nonlinear effects arising from errors in the superconducting coils are comparatively small, and
- 2) That radiation heating of the superconducting coils, as well as the potential for radiation damage are minimized.

The single bunch stacks from the accumulator are injected into the two ISABELLE storage accelerators by direct synchronous rf transfer in such a manner that a filling of less than 50% of the ISABELLE circumference is achieved. The rf bunch matching can be accomplished with less than 80% dilution, as shown in Fig. 11. However, even this small dilution can be eliminated with the aid of a higher harmonic cavity used as a "bunch match trimmer."

Fig. 11. rf Bunch Matching From Current Accumulator to the ISABELLE Storage Accelerators

Next, we consider specifically how we imagine the circumferences of the pair of ISABELLE rings will be filled. The process is described schematically in Fig. 12. In the filling configuration, the bunches do not collide. This is an important point. The beams can now be brought IN and OUT of collision slowly by relative rf phase adjustments. The frequencies in the two rings are, of course, synchronized exactly. This rf phasing technique allows the beam-beam interaction to be turned on slowly, allowing time to provide simultaneous tune and orbit adjustments. The collision configuration is sketched in the lower part of the figure. This procedure for collisions is in marked contrast to the unbunched ISABELLE case where beam separation must be accomplished by vertical displacement, in which case beam-beam turn-on and turn-off, being abrupt, is a rather subtle and sensitive process. Another feature of the rf phasing method is that it allows luminosity changes by simply changing the relative bunch phase. For example, a low luminosity configuration can be achieved by having nose-tail collisions.

Fig. 12. Azimuthal Beam Configuration at Different Stages for Bunched ISABELLE Operation With Current Accumulator

At this point I will give some attention to one of the more important aspects of the new scheme. I am referring to the impact on longitudinal impedance limitations. In qualitative terms, a beam of current within a vacuum tube induces electromagnetic fields which react back on the beam. This feedback could lead to antidamping of oscillations (that is beam instabilities), causing longitudinal beam growth (that is bunch length and momentum spread increase) and even current loss. The actual impedance is a property of the surrounding tube wall, while the limiting impedance or impedance tolerance is not, but rather depends on the beam character as well as on the magnetic properties of the ring (specifically, the transition energy).

Here is the argument for an accumulator based on longitudinal impedance limitations:

- 1) The impedance comes from chamber discontinuities which to a large degree are unavoidable. (They arise from the need for interfaces in the areas of vacuum, injection-ejection, rf and experiments).
- 2) The impedance tolerance is a sensitive function of beam and ring properties.
- 3) Rather than struggling to achieve perhaps unrealistically low impedances by wall design, it would seem to be more fruitful to optimize beam manipulation so that at each stage of beam operation the limitation placed on the impedance is a weak one.

Now, this is in fact exactly what the accumulator concept in our scheme accomplishes!

The limitation on impedance is usually quoted in terms of an impedance merit figure, which is essentially the maximum allowable impedance per unit length of machine. Specifically the figure of merit is $|Z/n|$, given by

$$|Z/n| = \frac{1}{2} \frac{\eta_p}{I_p} \left(\frac{\Delta p}{p} \right)^2 = \frac{1}{2} \frac{\eta}{p} I_p \left(\frac{\Delta p}{I_p} \right)^2$$

where $n = f_{\text{inst}}/f_{\text{rev}}$, the mode number for the instability
 I_p and $\Delta p/p$ are properties of the beam, and
 $\eta \approx 1/\gamma_{\text{tr}}^2$ is a property of the ring, with γ_{tr} the transition
 energy in proton mass units.

From this figure of merit, we can easily derive the rules for optimization:

- 1) Large rings lead to large γ_{tr} and so small η : they are bad
- 2) High density ($I_p/\Delta p$) beams are bad, and
- 3) For a given density, LOW currents are BAD

Conclusion: Since the fast accelerated beam from the AGS is high density and low current, then the worst way we can operate is to inject directly into a large ring (i.e. directly into the ISABELLE superconducting rings).

We can do much better by injecting this low current, high density beam into a small ring, the accumulator, and subsequently injecting the high current beams into the large rings, the ISABELLE main rings.

Quantitatively, the functional sequence we are proposing has a dramatic effect on the figure of merit, i.e. the longitudinal impedance tolerance, $|Z/n|$, as is clear from Table IV. Stacking directly into the ISABELLE superconducting rings leads to a $|Z/n|$ limit of about 4Ω , which means that the limit on the volume of discontinuity around the ring is very stringent. With the accumulator scheme, the situation is very different. For roughly equivalent performance, the tolerances are as follows: The accumulator can be designed to have a limit on the order of 50Ω (better than the ISR) simply because the transition energy γ_{tr} is about 3 times smaller in the accumulator than in one of the large ISABELLE rings. Now, since the ISABELLE rings need accommodate only the full stack, these will also have high merit figures even though γ_{tr} is high. It is found that the $|Z/n|$ limit for ISABELLE at injection is about 300Ω . Furthermore, with no dilution of the stack during acceleration, this drops only to about 70Ω at 400 GeV.

Table IV: Longitudinal Impedance Figure of Merit

	$ Z/n $	Limit	New
	No	Acc.	Scheme
		Ω	Ω
Accumulator	--		50
ISABELLE Rings - Injection	4		300
- High Energy (No Dilution)	30		70

Interaction Regions and Performance

Let me now consider a few points concerning the interaction regions and the performance potential of ISABELLE.

In our new approach, the luminosity can be increased by tighter bunching and not by lengthening the collision diamond with a crossing angle reduction. That is, to obtain higher luminosity:

- do not increase collision length as is the current ISABELLE method. (The high luminosity collision geometry is sketched in Fig. 13.)
- rather increase the peak/average luminosity by bunching.

Fig. 13. High luminosity collision geometry with no bunching (decreased crossing angle with large aperture common dipoles)

An immediate consequence is that the crossing angle becomes a fixed machine parameter - and no large common dipoles to reduce the crossing angle are required. (Bear in mind that these dipoles need an aperture of about 30 cm with beam moving near the aperture edge, at about ± 15 cm. The tolerances on magnetic field for such a magnet when used as part of a storage ring will be very tough to meet.) This trade-off can be seen another way by noting that for a given collision configuration the luminosity is proportional to $1/\alpha B$ and therefore we can reach higher average luminosities by decreasing the bunching factor, B (i.e. tighter bunches by rf voltage control) rather than by decreasing the crossing angle, α (i.e. longer collision length by using large aperture common dipoles). It follows in addition that with the new scheme, the full free space of ± 30 m around the crossing point becomes available for high luminosity experiments. In fact, we propose:

- that luminosity changes be accomplished by rf manipulation alone
- that the crossing angle be a fixed parameter, with no special bending magnets used to vary the crossing angle, and
- furthermore, that there be no focusing changes made so that the machine operates with a fixed magnetic structure and thus with essentially six-fold symmetry even for high luminosity experiments.

In the long bunch scheme, the "high luminosity" performance (Table V) is obtained with beams of average current 8 A. If we take a crossing angle of 14 mrad, a normalized emittance of $10 \pi \mu\text{rad m}$, and β values of 30 m horizontally and 5 m vertically, we obtain

- a luminosity at 400 GeV of about $1 \times 10^{33} \text{ cm}^{-2} \text{ sec}^{-1}$ with a peak to average value of 4.2
- a beam-beam tune shift of about 5×10^{-3}
- a collision length (4 rms lengths) of about 14 cm
- and a free space for experiments of ± 30 m.

Table V: High Luminosity ISABELLE Performance

Energy	400 GeV
Average Current	8 A
Peak Current	33.8 A
rms Beam Height	0.14 mm
Crossing Angle	14 mrad
Beam-Beam Tune Shift	5.1×10^{-3}
Collision Length (4σ)	13.7 cm
Free Space	± 30 m
Peak/Average Luminosity	4.2
Average Luminosity	$1.0 \times 10^{33} \text{ cm}^{-2} \text{ sec}^{-1}$

The relatively high tune shift for a 10^{33} luminosity is a result of giving up the "low β " configuration. Another consequence is that the luminosity becomes a function of energy which drops off somewhat faster than $\sqrt{E}$ as the energy is decreased.

When considering the operation of storage rings for high intensity and high energy, we must include in the design analysis

- 1) The stored energy in the beam, and
- 2) The synchrotron radiation which causes a continuous loss of beam energy during the storage cycle

Stored Energy in the 400 GeV ISABELLE Beam (See Table VI)

Table VI: Beam Stored Energy for 400 GeV ISABELLE

Average Current, I	8 A
Revolution Frequency, f_{rev}	74.3 kHz
Energy, E	400 GeV
Stored Energy per Beam ($W = IE/f_{\text{rev}}$)	43.1 MJ

The beam stored energy is just the energy per particle times the number of stored particles,

$$W = eNE = IE/f_{\text{rev}} = IE C_{\text{ISA}}/c$$

Thus, for a fixed current, I , the stored energy increases linearly with both circumference C_{ISA} and beam energy E and is, therefore, roughly quadratic with energy. For ISABELLE operating with 8 A at 400 GeV, the stored energy per beam is 43.1 MJ.

Now, one of the interesting dividends of operating with bunched beams is the simple fact that under normal operating conditions, more than 90% of the beam stored energy can be removed in a slow, controlled way by the rf system as the beams are decelerated. Thus, the fast removal of high beam stored energy by a material dumping system can to a large extent be avoided. (Of course, a "fast dump system" must be designed into the ISABELLE ring in any case for "emergency situations.") Also, "lossless" ejection can be envisioned with bunched beam operation because of the large azimuthal spaces between bunches.

Synchrotron Radiation From the 400 GeV ISABELLE Beam (See Table VII)

Table VII: Synchrotron Radiation 400 GeV ISABELLE Beam

Beam Energy, E	400 GeV
Magnetic Radius of Curvature, ρ	266.9 m
Circumference, C_{ISA}	$5 C_{\text{AGS}} = 4.036 \text{ km}$
Average Particle Power Radiated, P	0.18 GeV/h
Accelerating Voltage Required, V_s	0.68 V/turn
Critical Energy of Photon Emission, u_c	0.09 eV
Number of Particles in 8 A Beam, N	6.72×10^{14}
Average Beam Power Radiated, P_B	19.7 kJ/h
1% Damping Time, $\tau_{1\%}$	21.8 h

$$P = \frac{c C_Y E^4}{C_{\text{ISA}} \rho} (C_Y = 7.145 \times 10^{-18} \text{ m-GeV}^{-3})$$

$$V_s = P/f_{\text{rev}}$$

$$u_c = 3/2 c \hbar \gamma^3 / \rho (\hbar = 6.85 \times 10^{-16} \text{ eV} \cdot \text{sec})$$

$$P_B = NP$$

$$\tau_{1\%} = (0.01) P/E$$

As the energy of proton beams (used for storage over long periods of time) increases, the radiated energy from photon emission begins to have a measurable effect. This must be compensated. In a coasting, unbunched beam with no rf on, there is no way to avoid the beam energy loss. The radial movement of the beam can however be negated by decreasing the guide field proportional to the energy. On the other hand, in a bunched beam, the energy radiated can be recovered by the beam from the rf system. For the 400 GeV ISABELLE beam, the power radiated is 0.18 GeV/h per particle. This corresponds to an orbit shift of about 1 mm/h and so without compensation is not at all negligible. To compensate this energy loss with the rf system an accelerating voltage of about 0.7 V/turn is needed, a small amount indeed. The damping time for energy oscillations due to the synchrotron radiation is rather long, about 20 hours for a 1% decrease in energy spread. Thus, this damping is not useful as a counterbalance for slow growth processes such as intrabeam scattering, which has a 1% growth time of about 1 hour. The average beam power radiated from an 8 A beam is small, about 20 kJ/h or about 5 Joules/meter per hour. Since the photons are emitted in a very low energy region (the critical energy being about 0.09 eV), the total energy will simply be absorbed by the room temperature vacuum chamber.

Flexibility of Collision Energy with Bunched Beams

One of the key elements in the ISABELLE concept is the capacity to operate within a wide range of beam energies. It is not surprising then that the stack accelerating rf system should play somewhat of a dominant role in the operation of ISABELLE. However, the present design calls for debunching the stack before collisions and this represents a substantial loss in energy flexibility. On the other hand, remaining bunched during collisions retains energy flexibility even during the beam collision modes.

The type of energy flexibility that becomes possible with bunched beam operation is seen in the three examples of energy cycles in the figure on cycles (see Fig. 14). First, beam collision at a fixed energy is shown, and second, multiple collisions at different energies during a single cycle. In both these cases the bunches are kept out of collision during the periods when energy increments are made, with the second example depicting significant energy changes during a single operating period. Let me just remark here again that with this long bunch operation, under normal operating conditions, the beam will be decelerated to the injection energy and "lossless" ejection will then normally take place at low energy, important because it is a simpler procedure (less bending required); it minimizes radiation hazards, and it means much less beam stored energy need be deposited in a material dump.

Fig. 14. Energy Cycles for Bunched Beam Operation (Time Duration of Collisions is Arbitrary)

The third cycle shown involves continuous energy cycling while collisions are in progress. During this special cycle we visualize in particular a slow periodic cycling of the energy. This mode of operation could prove especially useful in experiments searching for new particle thresholds or in experiments attempting to measure small variations of reaction rate with collision energy. For example, prompt lepton production during cycling could be expected to give a distinctive threshold signature which is a function of the cycling rate, thus providing a new experimental handle in the search for the thresholds of the Z^0 , the $W^\pm$ and perhaps other new particles.

Table VIII summarizes some of the unique features of the new ISABELLE operating format being considered here. Much of this table I have already discussed, including

- 1) Minimal beam manipulation in the superconducting environment,
- 2) The high microwave $|Z/n|$ limit at all stages when stacking is performed in a separate "small" accumulator ring
- 3) The collision control by rf phasing, and
- 4) The fact that ejection, as well as beam scraping, can be performed at low energy.

Briefly, some other aspects of bunched beam operation are as follows:

- Since the beams are always bunched, conventional PUE's can be used for continuous closed orbit correction.
- Due to the bunch structure, electrons will not be trapped in the beam and there is therefore no threat of a coupled e-p instability. This implies that in principle no electron clearing electrodes are needed! And
- There are implications relating to the fact that the three bunches in each ring are truly independent. Thus, a "poor" bunch can be ejected and the beam renewed by injecting a "fresh" bunch in its place. Also, the background from distant intersections can be measured by colliding three bunches on two, for example. A third implication is that it is probably possible to operate each ring with BOTH high intensity and low intensity bunches simultaneously. It is even conceivable that alternating high and low luminosity collisions, differing perhaps by two orders of magnitude, could be developed. Finally, the new operating procedure would allow luminosity

Table VIII: Aspects of Bunched Beam Operation

1. Minimal Beam Manipulation

- Fast stacking and rebunching in acc. ring
- Minimal beam aperture utilization in ISABELLE
- Reduced effect of nonlinearities due to superconducting coils
- Minimal radiation hazards in ISABELLE

2. Microwave Instability

- $|Z/n|$ limit high at all stages

3. Collision Control by rf Phasing

- Slow, controlled IN and OUT by slow rf phasing
- Orbit, tune and chromaticity correction during operation
- Luminosity variation by phasing bunches (nose-tail collisions)
- Luminosity measurement performed during nose-tail configuration, where beam-beam (electromagnetic) interaction is very low (by Van der Meer method)
- Measure beam-gas background by phasing OUT of collision
- No undesirable vertical beam separation (difficult operation to collide and separate)

4. Normal Operation Ejection and Beam Scraping

- Routine ejection and beam scraping at "low" energy
- Deceleration trigger for monitored malfunctions
- Most of beam stored energy absorbed by rf during deceleration

5. Beam Position Observation

- With bunched beam, conventional PUE's for continuous closed orbit correction

6. Electron Clearing

- Self-clearing due to bunch structure
- No e-p instability
- No clearing electrodes (in principle!)

7. Three Bunches Independent

- Eject a "poor" bunch for beam "renewal"
 - Measure background from distant intersections by colliding three bunches on two, for example
 - Operate with high and low intensity bunches simultaneously, leading to alternating high and low luminosity collisions.
 - Luminosity measurements during nose-tail collisions when beam-beam interaction small, that is with conditions the same as during physics runs. Different from ISR where special low intensity operation is required.
-

measurements with beam and ring conditions the same as during physics runs. They can be performed simply by phase adjustment to create nose-tail collisions so that the beam-beam interaction is small enough to allow the Van der Meer process to be employed. This has a clear advantage over the ISR, where special low intensity operation is required for luminosity measurements.

Super-ISABELLE - The COSMICTRON

Super-ISABELLE or the COSMICTRON can be viewed as an extrapolation of the ISABELLE concept. In Table IX, we see its proposed gross parameters: 12 km circumference, an average current of 8 A, and reaching an energy of 2 TeV with a 60 kG magnetic field. The normal cells are lengthened as compared to ISABELLE to about 90 m, each containing fourteen 5 m dipoles, with six straight sections each about 300 m long.

Table IX: COSMICTRON Parameters

Circumference, C_{cos}	12 km (3 C_{ISA})
Injection Energy	400 GeV
Top Energy	2 TeV
Top Magnetic Field	60 kG
Average Current	8 A
Momentum Spread, $(\Delta p/p)$ (Injection)	0.2 %
Momentum Spread, $(\Delta p/p)$ (Top Energy)	0.04 %
Bunching Factor	0.25
Peak Current	32 A
Beam Size at Injection (max, cell)	1.2 cm
Beam Size at Top Energy (max, cell)	3.3 mm

Some Major Features are as Follows:

- 1) The beam size is small, 1.2 cm at injection, and shrinking to 3.3 mm at 2 TeV. This small beam size leads to the possibility of using small aperture magnets. The cost per unit length of machine should then be substantially reduced. Perhaps with advances in

superconducting technology the cost of the COSMICTRON will not be much different from the ISABELLE cost.

2) The COSMICTRON performance should be comparable to that of ISABELLE (as can be seen from Table X) except that the free space for experiments has been doubled to $\pm 60 \text{ m} = 120 \text{ m}$. The crossing angle for the performance shown is 10 mrad.

Table X: High Luminosity COSMICTRON Performance

Energy	2 TeV
Average Current	8 A
Peak Current	32 A
rms Beam Height	0.11 mm
Crossing Angle	10 mrad
Beam-Beam Tune Shift	5.1×10^{-3}
Collision Length (4σ)	12.3 cm
Free Space	$\pm 60 \text{ m}$
Peak/Average Luminosity	4.0
Average Luminosity	$1.8 \times 10^{33} \text{ cm}^{-2} \text{ sec}^{-1}$

3) For a 2 TeV, 8 A beam, the beam stored energy is 640 MJ (see Table XI). It is certainly a fair question to ask how such a large beam stored energy can be removed safely. The answer is far from clear. However, one possibility, as has been intimated before, is that we can remove most of the stored energy with the rf system by deceleration. In assessing the "coasting vs bunched beam" choice, this possibility could be an important factor. We can even envision deceleration triggers where deceleration is initiated under certain malfunction signals of the complex. Thus, only under unusual or extraordinary emergencies would a dumping of the full beam energy into a material dump be required. Perhaps never?

Table XI: Beam Stored Energy for 2 TeV COSMICTRON

Average Current, I	8 A
Revolution Frequency, f_{rev}	25.0 kHz
Energy, E	2 TeV
Stored Energy per Beam ($W = IE/f_{\text{rev}}$)	640 MJ

4) At 2 TeV, the energy loss from synchrotron radiation in the COSMICTRON is about 9 GeV/hour (see Table XII). With bunched beams, this energy loss is, of course, supplied by the "holding" rf system. The needed "accelerating" voltage is about 100 V/turn. For bunched beams, then, the top energy, 2 TeV, can be maintained for many hours. However, for a coasting stack there is naturally a slow energy reduction in each beam at the rate of 9 GeV/h or about $\frac{1}{2}\%$ per hour. The 2.7 eV photon emission will be completely absorbed by the vacuum chamber. The 800 W power is distributed over about 7 km, i.e. about 0.1 W/m, which is easily absorbed and dissipated in a room temperature chamber wall. The 1% damping time in the COSMICTRON is about 2 hours, which is small but not entirely insignificant. In fact, such a damping time could provide some measure of protection against diffusive type processes such as intra-beam scattering.

Table XII: Synchrotron Radiation 2 TeV COSMICTRON Beam

Beam Energy, E	2 TeV
Magnetic Radius of Curvature, ρ	1111.9 m
Circumference, C_{cos}	$3 C_{\text{ISA}} = 12 \text{ km}$
Average Particle Power Radiated	9.25 GeV/h
Accelerating Voltage Required, V_s	102.8 V/turn
Critical Energy of Photon Emission, u_c	2.69 eV
Number of Particles in 8 A Beam, N	2.0×10^{15}
Average Beam Power Radiated, P_B	2.96 MJ/h = 822.6 W
1% Damping Time, $\tau_{1\%}$	2.1 h

Review

A scheme has been presented which consists of a sequence of steps with each step performing a function in addition to acting as an injector to a subsequent step. The ultimate aim of the sequence is to obtain high current and high energy for proton-proton collisions. Let me review the steps:

Step 1 is a "fast" cycling energy booster; it acts as an injector for a current accumulator at 30 GeV (see Fig. 8).

Step 2 is a current accumulator, capable of stacking more than 10 A current. It might also be capable of slow accelerating the 10 A single bunch stack from 30 to 50 GeV; it acts as an injector for the 400 on 400 ISABELLE (see Fig. 8).

Step 3 is the pair of ISABELLE storage accelerators, capable of storing a high current stack of 8 A in three bunches in each ring. It is also capable of slowly accelerating the beams from 50 to 400 GeV. The pair of rings act as injectors for the COSMICRON (see Fig. 9). Just as the current accumulator is a marvelous injector for ISABELLE, so ISABELLE is an ideal injector for a super-ISABELLE. The COSMICRON, therefore, becomes the next step.

Step 4 of the complex is the COSMICRON and is conceived to be a larger (three times the ISABELLE circumference or 12 km), higher energy (five times the ISABELLE energy or 2 TeV), set of storage accelerators. In fact, it can be thought of simply as a scaled up ISABELLE, except built with more compact, smaller aperture, and so cheaper magnets. One might hope that with advances in superconducting and cryogenic technology such an addition to the storage ring complex at BNL would not cost appreciably more than ISABELLE itself. Therefore, if high luminosity collisions (about 10^{33}) in the center-of-mass energy region of 4 TeV is the desired goal of the high energy physics community, it is not impossible to imagine a construction start by the late 1980's and thus a real COSMICRON in the mid 1990's. It could happen!

Acknowledgments

I would like to thank J. Claus, J. Humphrey, M. Marx, and especially J. Herrera for their collaboration in the performance of this work. I would also like to express my appreciation to P. Mohn for his aid in drawing the site figures and J. Ferrero for preparation of the manuscript of this lecture.

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