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PROPOSAL FOR A TEST OF LOW INTENSITY EXTRACTION FROM THE TEVATRON USING CHANNELING IN A BENT CRYSTAL

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ABSTRACT

During the 1992 collider run of the Tevatron, we propose to insert a bent crystal at the B-48 location in the Tevatron and extract a low intensity beam into the abort channel at C0. Our goal is to extract 10^{-6}/sec of the circulating beam (less than 10^6 protons/sec with a circulating beam of less than 10^{12} protons). An off-momentum halo will be generated, and the extraction rate controlled, by deliberately generated, filtered RF noise or RF modulations at discrete frequencies. The experiment tests the feasibility of this technique as an extraction mechanism for the SSC for the SFT B-physics facility described in SSC EOI-14. It will also test the general effectiveness of bent crystals used as halo scrapers for the CDF and D0 experiments. About 100 hours of dedicated Tevatron time are requested to establish the technique, during which only protons need to be circulating.

INTRODUCTION

Low-intensity extraction from the SSC using a bent silicon crystal has been discussed for many years at summer studies (see, for example, Cox et al. Snowmass 88 and references therein[1]). Crystal extraction in the GeV range has already been demonstrated at Dubna[2] and Serpukhov[3]. Recently, an experiment has been proposed for the SSC (EOI-14) to utilize a low-intensity extracted beam to study B-physics in the fixed target mode, called "SFT" ("Super Fixed Target"). For the SFT experiment, it is necessary to extract about $2*10^8$ protons/sec, a fractional extraction rate of $2*10^{-6}$/sec of the circulating beam (which we take to be 10^{14} protons).

The response of the SSC Physics Advisory Committee to the proposed experiment was most favorable, including the statement (from the "Summary of the Meeting and Recommendations", July, 1990):

> "...it would be desirable to incorporate B-physics into the initial SSC program.... For the initial SSC program, a fixed-target experiment may prove a better choice [than a collider detector]."

The PAC Committee also recommended (as conveyed in a letter from Schwitters to B. Cox, dated July 31, 1990) that:

> "...tests on the viability of the proposed crystal extraction scheme deserve a high priority within this context. In particular, a test at Fermilab in a realistic environment was deemed as one appropriate course of action that would hopefully give us some hard evidence on the likelihood of the extraction technique working at the SSC."

During the last year, much theoretical progress has been made on both the multi-turn efficiency of a bent crystal to extract beam and the use of RF to move beam particles from the edges of the longitudinal and transverse phase spaces onto the crystal. Much attention has been paid to the criterion that this extraction process not degrade the luminosity lifetime of the SSC collider experiments in a significant manner. In addition, more experimental data has come available from the Aarhus-CERN experiments at CERN[4] showing the effectiveness of bent silicon crystals in deflecting high energy proton beams. At this point, the groundwork has been laid for a realistic test of such crystals as an extraction technique for the TeV range.

We propose to test the complete extraction scheme as discussed below experimentally, with parameters in the Tevatron experiment selected such that the results can be credibly scaled to the SSC.

This effort will also have benefits to both the Tevatron and the SSC in understanding and getting rid of the natural halo which is detrimental to the collider experiments. At the Tevatron, it is only in the last few years that studies by S. Pruss and others have begun to yield some information on the important subject of beam halo. An ancillary benefit of this experiment is that it might result in more valuable information on beam halo that could have a beneficial effect on reducing halo at the collider detectors. At the SSC, our extraction crystal is being considered as the first scraper in a scheme being designed for the East Utility Straight Section.

THE SSC EXTRACTION PROPOSAL

In order to understand how the Tevatron experiment will scale to the SSC, the SSC proposal must first be understood. This is well documented in the report of the SFT working group that will appear in the Snowmass 90 proceedings[5] included as an appendix to this proposal. In summary, a bent silicon crystal is put in the SSC East Utility straight at a high-dispersion point (D = 4 m) to deflect off-momentum halo particles up into the field-free region of a Lambertson magnet string 250 meters away (see Figure 1). The circulating beam is deflected back to the normal orbit by the field region of the Lambertson magnet string. Planar channeling in the (110) planes will be used.

In the SSC, the upward bend angle of the crystal is 100 microradians, and the crystal length is in the range 3 to 5 cm, a region in which the various crystal inefficiencies are minimized for multi-turn extraction. Crystal inefficiencies due to bending are believed to be a universal function of only P/R, where P is the momentum of the beam in GeV/c and R is the radius-of-curvature of the crystal[6]. This ratio is 1/2 GeV/cm for a 4 cm crystal with the above bend angle.

The crystal edge is positioned 1 mm away from the center of the circulating beam in the horizontal plane, which is 4 standard deviations from the center of the on-momentum beam. Since the edge of the RF bucket is at dP/P = 0.00025, this crystal location also corresponds to the center of particles with the maximum allowed dP/P, since the dispersion function at the crystal is 4 m. However, the standard deviation of the momentum distribution is 4 times smaller than the bucket edge. A good measure of the extent to which the total x distribution is dominated by dispersion or the on-momentum x-distribution is the ratio $\sigma(dP/P)*D/\sigma(x)$, which is 0.82 for the SSC.

The natural rate of halo generation onto a crystal at this location, from beam-gas collisions and collisions of the crossing beams, is expected to be only around 10^7/sec, with 10^{14} protons circulating[7]. To obtain the necessary 10^8/sec, RF modulations or

RF phase noise will be added at the SSC in order to preferentially move particles which are on the edge of the longitudinal phase space to higher dP/P orbits. Particles enter the crystal when they have been boosted in momentum, and they come preferentially (but not entirely) from the tail of the transverse phase space (x,x'). The purpose of this type of RF modulation is to minimize the disturbance of the core of the beam so as to preserve high luminosity at the collider interaction regions.

Several RF manipulation schemes have been quantitatively studied, and two of them look especially promising. Filtered RF phase noise limited to two frequency bands, the one at less than the synchrotron frequency and the other just above the revolution frequency, has been simulated in a Monte Carlo program[8]. It is called "notched noise", and the results indicate a quite adequate extraction rate with an adequate "step size" (a few microns) into the crystal. The "step size" is the depth in the crystal at which a circulating proton first hits the crystal.

Two-frequency amplitude modulation has also been studied[9]. A "drive" frequency at 1.5 times the small-oscillation synchrotron frequency resonates with particles near the edge of the RF bucket and drives them rapidly to even higher orbits, onto the crystal. A varying "feed" frequency, weaker in amplitude in the frequency range 1.5 to 2 times the synchrotron frequency, resupplies particles to the "drive" frequency resonance. The results look promising. We propose to test both methods of manipulating the beam with RF, and perhaps other methods which are still under study.

THE TEVATRON PROPOSAL

The C0 straight section in the Tevatron is used for a high-intensity proton abort during fixed-target operations, but will be unused during collider operations, starting with the 1992 collider run (both collider aborts are at A0). It has many properties analogous to the proposed SSC insert-a horizontal 3-bend dogleg of which the center bend is Lambertson magnets, and large dispersion (D = 2.9 m) at the position of the abort kicker magnets (see Figure 2). This is no accident, since our SSC dogleg insert is a copy of the SSC abort insert, and the SSC abort was modeled after the Tevatron abort[10]. The four abort kicker magnets at B-48 deflect the beam up 600 microradians so that the entire beam goes through the field-free hole of the Lambertsons to the beam dump.

We propose to replace one or more of the kicker magnets for the duration of the 1991 collider run with a bent crystal assembly and ancillary equipment, and count protons deflected into the abort channel as a function of the parameters of the RF manipulation scheme being used. To keep the same P/R ratio as for the SSC, the crystal length should be 1.1 cm for a 600 microradian bend angle. In order to put the crystal edge at the maximum dP/P contained by the RF bucket (dP/P = 0.0006), the edge of the crystal would be placed 1.75 mm from the center of the circulating beam in the horizontal plane.

In order to simulate the SSC fractional extraction rate (10^{-6}/sec of the total number of circulating protons), and also have an extracted beam which can be counted by scintillators and other detectors, we require that the extracted intensity be less than a few times 10^6/sec, and that the number of protons extracted from each RF bucket be somewhat less than 1, how much less depending on RF structure. If we take this number to be 0.2, this leads to the requirement that the number of circulating protons per bunch be less than $1*10^{10}$. Since the natural collider mode has either 6 or 36 RF buckets filled, we note that 36 bunches of $1*10^{10}$ each is nearly ideal, leading to an extraction rate of $0.36*10^{-6}$ protons/sec. The exact choice needs more detailed discussion with Tevatron experts.

A list of various properties of the beams and crystals for the SSC and the Tevatron are shown in Table I.

TABLE I

Properties of the Circulating Beams
and the Crystals for the Tevatron and the SSC

Property	Tevatron	SSC	Units
emittance(1σ)	$3.33\pi/P$	1.0	
β_x	98	1320	m
β_y	28	517	m
α_x	-0.1	1.72	
α_y	-0.1	0.68	
σ_x	0.60	0.26	mm
σ_y	0.32	0.16	mm
$\sigma_{x'}$	6.2	0.39	μrad
$\sigma_{y'}$	11.5	0.37	μrad
$\delta P/P_{max}$	0.00060	0.00025	
$\sigma_{\delta p/p}$	0.00020	0.00005	
D(dispersion)	2.9	4	m
$\sigma_{\delta p/p}\cdot D/\sigma_x$	0.97	0.78	
$L_{crystal}$	1.1	4.0	cm
Θ_{bend}	600	100	μrad
P/R	0.5	0.5	GeV/cm
ϕ_{crit}	5.2	1.1	μrad
$\phi_{crit}/\sigma_{y'}$	0.45	3.0	
$x_{crystal\ edge}$	1.75	1.0	mm

We note that the ratio of the dispersion to the natural x width [$\sigma(dP/P)*D/\sigma(x)$] is very comparable for the two machines. However, the ratio of the crystal critical angle to the vertical angular divergence ($\phi_{crit}/\sigma(y')$) is somewhat less favorable for the Tevatron, a result of both the larger emittance and the larger gamma function value (see Figure 6 in the appendix). Only particles with y' less than ϕ_{crit} are channeled, so this low ratio implies that perhaps only 30% of the Tevatron beam would be channeled on the first turn in which it was incident on the crystal (in comparison with about 70% for the SSC). However, particles not channeled on the first traversal of the crystal have several more opportunities, on later turns, to come back with a smaller vertical angle and get channeled before they have been deflected out of the acceptance of the machine by the accumulation of multiple coulomb and nuclear scattering in the crystal. A full simulation, including the multi-turn Monte Carlo, is planned using the same programs currently in use for the SSC analysis.

CRYSTAL POSITIONING AND INSTRUMENTATION

The crystal will be mounted in a goniometer and pre-bent to 600 microradians. The crystal will be fully retracted from the Tevatron aperture during injection and acceleration. After it is brought in close to the 900 GeV beam, its vertical and horizontal angles must be mechanically aligned to match the beam angles. Therefore, the goniometer must be capable of remote angular adjustment through microradian-level angles. In the horizontal plane, the crystal face perpendicular to x must be parallel to the beam to considerably less than the average "step size" (see above) of the particles being swept onto the crystal by the RF modulations. This is entirely analogous to the electrostatic septum wire alignment problem for resonant extraction. Since the average step size is only a few microns, alignment to about 1/2 micron over the 1 cm length is needed, or an angular least-step size of about 50 microradians in the goniometer. The crystal face also has a "septum width" (analogous to the wire thickness for electrostatic septa) because of the impossibility of polishing it perfectly flat. Optical flatnesses of about 0.1 microns are achievable[11].

Because the atomic planes of the crystal must be aligned parallel to the beam within the vertical angular divergence of the beam, the least-step size of the goniometer angle would need to be on the order of 10 microradians. A step size five times smaller was achieved in Fermilab E-761. In addition, the vertical trim magnet system of the Tevatron is easy to program to make small angular adjustments at the crystal (with no position change at the crystal), should that technique prove easier.

The front and back ends of the crystal will be implanted with fully depleted solid state detectors which measure dE/dx of particles entering and leaving the crystal. As illustrated in the recent CERN experiment[4], the most probable energy loss for channeled particles is only about 1/2 the energy loss of unchanneled particles, so one can potentially measure the fraction of particles channeled both initially and after deflection. It may be possible to use these detectors to measure the channeling efficiency and also to help with the crystal alignment process. The appearance of the full energy-loss signal on the crystal proves that there is incident beam before any channeling has been achieved. The alignment process is then a two dimensional scan searching for the half-energy signal.

The planned two-dimensional scan will be highly automated. Furthermore, since one does not want to repeat the full two-dimensional scan at the beginning of each fill of the Tevatron, the goniometer retraction mechanism will be designed to be sufficiently precise so as not to lose the goniometer orientation during retraction. A small scan will probably be necessary at the beginning of each session, since the tuned orbit of the Tevatron drifts from day to day at the 20 microradian level.

INSTRUMENTATION OF THE EXTRACTION CHANNEL

We plan to count and measure the spacial extent of the extracted beam after it leaves the crystal and separates from the circulating beam. There is a 35 m drift space following the Lambertson magnets before the abort line leaves the tunnel which can be used for this purpose. At the end of this drift space, the abort line and the circulating beam are separated by about 1 meter, adequate to separate the extracted beam from backgrounds associated with the circulating beam. We propose to insert scintillators and silicon strip detectors, borrowed from fixed target experiments, in this space to measure the shape and intensity of the extracted beam.

GOALS OF THE TESTS

In this test, we plan to investigate: 1) RF manipulations necessary to put beam on the crystal in a controlled way. 2) The alignment techniques for the crystal. 3) The level of coupling of the extraction system to the collider experiments, for instance, the impact of this extraction on the background and beam size at the experiments.

HOURS REQUESTED

We envisage these studies to be done in a series of 12-hr shifts during machine study periods. From experience at Fermilab with bent crystal experiments we estimate that about six such sessions, separated from each other by at least a week, are necessary to prove the technique.

After we are successful in this first effort, we may request to use our remaining allotted time to operate the system during colliding beam operations, both to verify our expectations that neither CDF nor D0 can detect our activity, and to test the idea that our bent crystal can be a halo monitor for collider operations.

WORK IN PROGRESS

Further work is in process on the details of this test. These items are: 1) A specific design for the crystal and goniometer. Work has already begun on this matter by several teams who have previously built crystal goniometers. 2) A specific plan for RF manipulations. Discussions with Fermilab accelerator scientists indicate that the necessary RF equipment is in place already. However, further investigation may indicate that some additional equipment would be desirable. It is expected that any such equipment would also serve a useful purpose for other RF studies. In addition, other RF modulation schemes are being studied. 3) Details of the instrumentation of the 35 m abort channel. We believe that this is the simplest matter to plan, as we will bring all the necessary detectors, electronics, and cables from fixed target experimenters. We note that C0 was the scene of E-735 and is equipped with cable trays and a counting house. Furthermore, several of the participants in this experiment were members of E-735 and are quite familiar with the territory.

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4. S. P. Moller et al., Phys. Lett. B256, 91 (1991).

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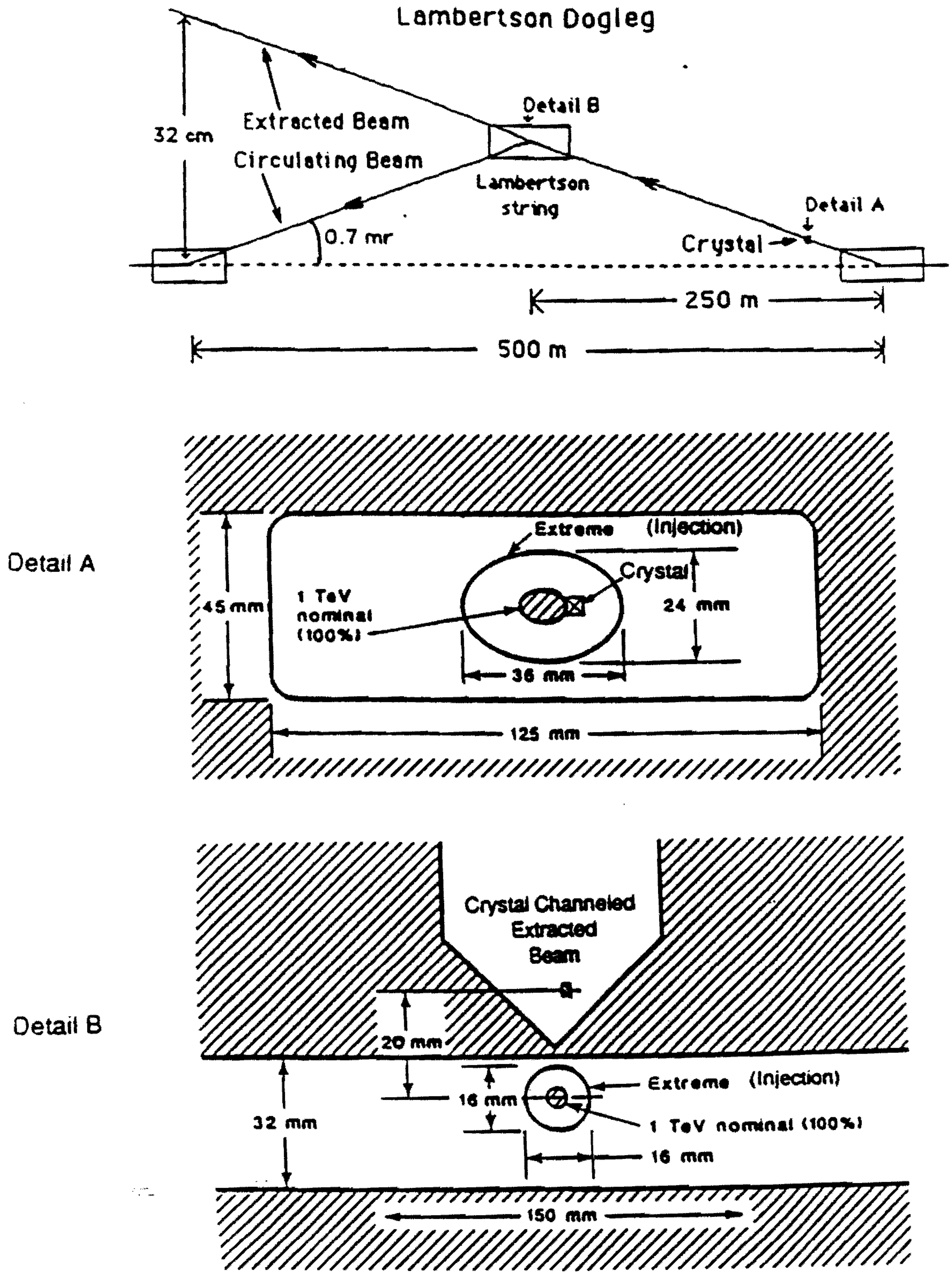
FIGURE CAPTIONS

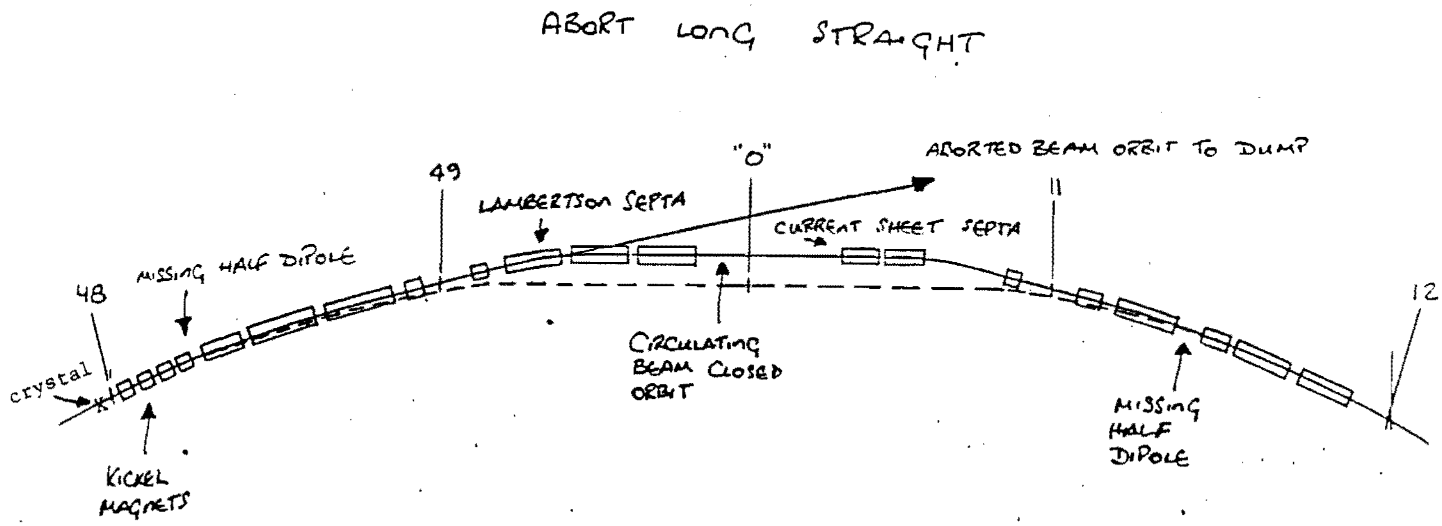
1. Lambertson magnet dogleg and channeling crystal configuration for the SFT extraction system at the SSC.

2. C0 Tevatron abort schematic.



.. Lambertson Magnet Dogleg and Channeling Crystal Configuration for the SFT Extraction System

Figure 1



ABORT LONG STRAIGHT
ABORTED BEAM ORBIT TO DUMP
"0"
49
LAMBERTSON SEPTA
CURRENT SHEET SEPTA
11
MISSING HALF DIPOLE
48
12
crystal
CIRCULATING BEAM CLOSED ORBIT
MISSING HALF DIPOLE
KICKER MAGNETS

Figure 2

Report of the Super Fixed Target Beauty Facility Working Group On Progress Towards the SFT at the SSC

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Abstract

A low intensity 20 TeV proton beam extracted from the SSC by crystal channeling has been proposed for use in producing B hadrons in a fixed target configuration. This option for doing B physics offers a relatively inexpensive way of obtaining large numbers of reconstructable B decays for the study of rare B decays and CP violation in the B system. This paper reports on the progress during and since the 1990 Snowmass meeting in developing the techniques for the crystal extraction and discusses special advantages that an SSC fixed target spectrometer may have relative to other experimental methods for studying B decays.

I. Introduction

The determination of the CP violating phase of the 3x3 Cabbibo-Kobayashi-Maskawa mixing matrix by measurement of its elements in a variety of weak B decays is the most compelling reason for the study of B physics. However, the rare decays of the B mesons and baryons are also very important since their study may open windows on physics far beyond that which is accessible to direct observation. The electroweak Standard Model will be challenged in both these areas by precision measurement of B decays. Tests of whether the unitarity condition for this matrix is satisfied will allow testing of the number of quark and lepton generations independent of neutrino mass. In addition, the opportunity to measure CP violation in a different sector of the CKM matrix, B decays provide a vantage point which will shed light on the origin of time reversal violation.

The unitarity condition for the CKM matrix

$$V^*_{ub}+V_{td} = |V_{cd} V_{cb}|$$

can displayed as a triangle in the complex planes whose sides are the CKM matrix elements as shown below.

The various angles of this triangle can be determined from the measurements of CP violation in a variety of different exclusive B

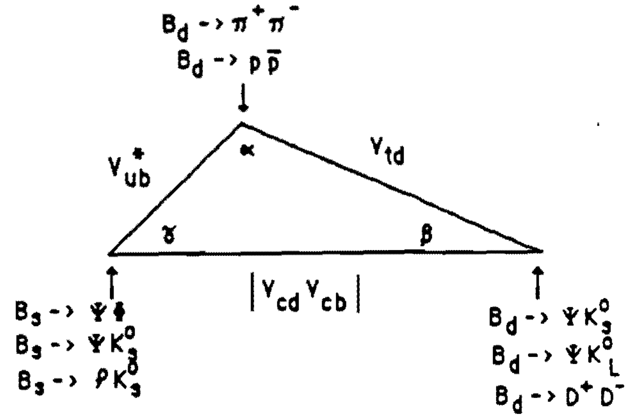


Fig. 1. CKM Matrix Unitarity Triangle

decay channels, some of which are shown in Fig. 1. The ability to collect large statistics in these important decay channels in a given experimental approach plus the ability to tag the decaying hadrons as B or $\overline{B}$ are coupled criteria that must be examined for any proposed method of studying B decay. As we will see the fixed target approach performs well when judged against both these requirements for performing B physics.

Provided that one can successfully accomplish the measurement of some of the angles or sides of this triangle, one can check the validity of the assumption of the existence of the triangle and extract information from its shape. The closure of this triangle will be indicative of only three generations (modulo the accuracy of the measurements of the CKM matrix elements), and a non zero height of the triangle (non zero β and γ) is evidence for CP violation.

The level of CP violating effects are predicted to be very large from the relationship between CP violation in the K and B system implied by the existence of the CKM matrix and its unitarity triangle. CP violation which will show up as differences in particle and antiparticle branching ratios or time distributions in various specific exclusive decay modes can be as large as a few to several tens of percent asymmetries between partic[le] and antiparticle behavior in many exclusi[ve] decay channels. This is very large compared [to] the relatively tiny effects observed in the K system. However, in spite of the large asymmetries expected in the B decays, large numbers of B's must be produced in order to get statistically significant measurements in the various exclusive B modes. In addition, by definition, rare B decay modes will require large numbers of reconstructed B decays for their study. The reasons for the requirement for large numbers of produced **and reconstructed B's are manifold.**

1. There are many species of B hadrons (B_d, B_u, B_s, B_c mesons plus the B baryons) which share the produced b quarks, thus reducing the statistics in a particular exclusive B decay mode such as $B_d > \Psi K^0_s$.

2. There are many decay modes open to the relatively massive B hadrons. In addition, the B decay products include relatively massive objects (charmed hadrons) which themselves have many accessible decay modes. This leads to complex decay chains, any one of which has a relatively low probability. A composite branching ratio of order 10^{-4} for a specific exclusive B decay chain in which we might desire to study CP violation is relatively large because of these factors. Rare decays of interest are also expected to be at maximum at this level under optimistic assumptions.

3. To the usual experimental factors that decrease statistics in any particular mode such as geometric acceptances, chamber and counter efficiencies and trigger efficiencies, additional factors due to the necessity of separating secondary vertices from the primary vertex must be added. In some cases there are cuts due to the requirements of distinguishable tertiary vertices due to charm meson decay. This vertex pattern recognition process is only the first step in the pattern recognition process. In addition, to completely reconstruct a specific final exclusive decay, the correct assignment of a given track to a particular vertex must be made. This cannot be done with 100% efficiency. The neutral decay products pose a special experimental problem, inasmuch as the connection between a given secondary vertex and the neutral decay product cannot be established by a track in the microvertex detector.

4. To detect CP violation any sample of B decays must be divided into particle and antiparticle samples (tagged), thereby reducing the statistics in either the particle or antiparticle samples by the need in most cases to detect and, at least, partially reconstruct the "other" B decay in the event under study.

The composite effect of these various features of B decay leads to factors of 10^6 or greater between the number of B's produced and the number of B's that can actually be reconstructed and tagged in a specific exclusive decay chain (presumably one in which a large asymmetry is expected). This factor, in turn, leads to the requirement that we produce at least 10^9 $B\overline{B}$ pairs to achieve adequate statistics for a three sigma measurement of a 10% asymmetry between particle and antiparticle decay rates in a given exclusive mode. By even simpler arguments, studies of rare decay modes with branching ratios of 10^{-5} or less will require the same level of statistics.

These large factors make individual strategies for the measurement of CP violation in specific decay modes quite experiment dependent. However, the factors given above put a premium on producing large numbers of B's in any experiment whether symmetric or asymmetric e^+e^- B production at the $\Upsilon(4s)$ or B hadroproduction in the various experimental configurations. The earlier work[1,2] and the work reported on in this paper make it clear that a fixed target experiment at the highest possible beam energies (20 TeV at the SSC) is a very economical and efficient way of producing large numbers of B's (10^{10} to 10^{11} B pairs per year at 10^7 interactions per second), a significant fraction of which can be reconstructed. In addition, a facility of this type would offer the special advantage of being able to observe and measure the B's directly, an opportunity available to no other technique so far advanced. This greatly enhances the tagging of B decays by direct observation of the B_u tracks. For these reason, an SSC fixed target B hadroproduction facility is a very attractive option for the future for precision studies and measurement of CP violation

II. B Production in Hadroproduction Experiments

Since experimental results for B hadroproduction cross sections are still not very precise in most energy ranges, we must depend, at the present, on theoretical estimates of the heavy flavor production. Calculations of the B hadroproduction cross section to third order in α_s performed by K. Ellis, S. Dawson and P. Nason[3] are shown below as a function of $\sqrt{s}$ in Fig. 2. More recently calculations of this cross section including corrections due to higher orders have been performed by Collins and Ellis[4]. The calculation including large order corrections produces a cross section somewhat larger at 20 TeV fixed target energies than the 3rd order result.

This calculation agrees within errors with the limited experimental data that exists to date on B hadroproduction. The cross section increases rapidly from the 10 nb level in present Fermilab fixed target pN interactions ($\sqrt{s}\approx38$ GeV) to the one to ten microbarn range for an SSC pN fixed target experimental configuration ($\sqrt{s}\approx193$ GeV). The rate of increase of the cross section with energy diminishes beyond 193 GeV so that at the present Fermilab collider energy(1.8 TeV), the B hadroproduction cross section has only increased by a factor of 20 relative to the SSC fixed target option. Extrapolating to SSC collider center-of-mass energies (40 TeV) results in a further increase of approximately 2 to 3 in the B cross section over the Fermilab collider cross section.

However, the absolute value of the B hadroproduction cross section is only one of the factors that indicates how effective a given B hadroproduction experimental configuration really is. In fact, more important than the absolute value of the B hadroproduction cross section is the ratio of of that cross section to total cross section, given that all hadroproduction experiments are ultimately limited by the number of interactions per second that the spectrometers can accommodate. By this criterion, fixed target experiments gain because, while the B production cross sections are lower in the fixed target configurations, so are the total cross sections. Indeed, the total cross section at $\sqrt{s}\approx193$ GeV is approximately 32 mb, approximately 1/3 of that at $\sqrt{s}=40$

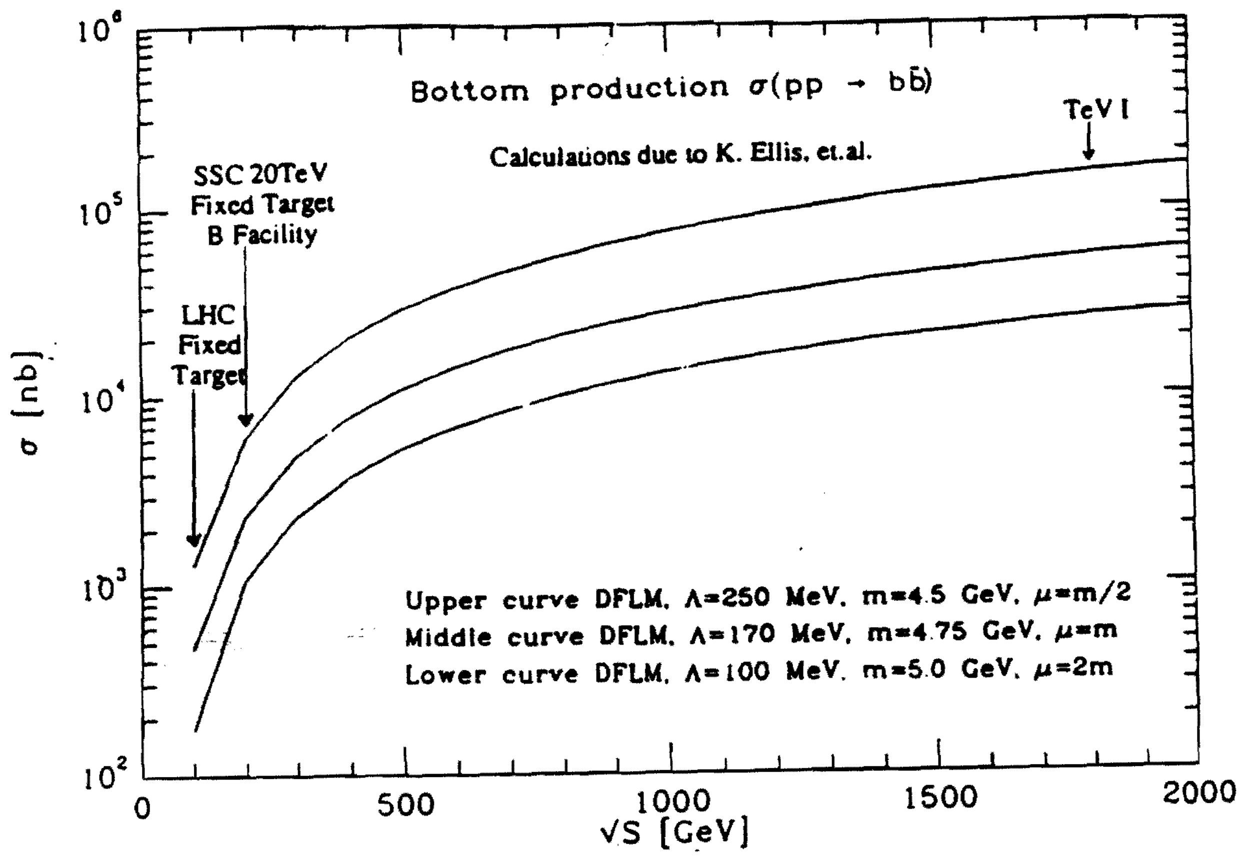


Fig. 2. Third Order Calculation of the B Hadroproduction Cross Section in pp Interactions as a Function of $\sqrt{s}$

TeV. In addition, the ratio of cross sections in fixed target experiments are enhanced by nuclear target effects in heavy flavor production. The total cross section at Fermilab fixed target energies has been measured[6] to have an A dependence of $A^{0.72}$ while the B hadroproduction cross section is expected to scale like A^1 leading to factors of 2.5 (Si target) to 4.3 (W target). The combination of these two effects tends to bring the ratio of B production to total cross section much closer to that expected in a collider configuration at 40 TeV than might otherwise be expected. As seen from Table I, the ratio of B production to total cross section for a pSi experiment at 20 TeV is expected to be between 1/2300 and 1/7600 interactions, compared to 1/200 to 1/500 in 40 TeV pp interactions, only a factor of 10 to 15 in favor of the collider configuration.

In addition, there are several major advantages of the fixed target configuration in triggering, tagging, complete event reconstruction and simplicity of the spectrometer which more than compensate for this slight advantage of the collider configuration in ratio of gross B production to total cross section. These advantages arise from the dynamics and kinematics of B production in a fixed target configuration. In particular, the Lorentz boost of a SSC fixed target experiment produces much higher momentum B's (average ≈ 445 GeV/c) than those produced in an SSC collider configuration. In addition, the B's and their decay products are confined within a relatively small laboratory solid angle. This small solid angle permits a relatively simple and inexpensive spectrometer to capture all decay products of a relatively large fraction of the B's. Indeed, 50% of B's produced in 20 TeV pN interactions have all their decay products contained within a 3 mr to 75 mr cone.

In addition, the small angles of the decay products allows for a relatively simple planar microvertex detector. The SFT silicon vertex detector can have many more measurement planes (120 - 200 micron planes) because the very high momentum of the B's (and hence of their decay products) results in negligible multiple scattering. Because of the low multiple scattering and the lack of need for a beam pipe in the fixed target configuration, the microvertex detector can be configured as a live target. These closely packed silicon planes

Table I

Important Parameters of Hadronic Beauty Production

	FNAL Fixed Tgt	FNAL Collider	SSC Collider	SSC Fixed Tgt
Int Rate	10^7-10^8/sec	10^5/sec*	10^7/sec**	10^7/sec
$\sigma(pN \to B\overline{B})$	10 nb	20 μb	200-500 μb	2.5-10 μb
$B\overline{B}/10^7$ sec	10^7-10^8	4×10^8	2×10^{11}-5×10^{11}	1×10^{10}-5×10^{10}
$\sigma(B\overline{B})/\sigma_T$	1/1250000***	1/2500	1/500-1/200	1/7700-1/1900***
Multiplicity	≈15	≈45	"few" hundred	≈20
$\langle p_b \rangle$	143 GeV/c	38 GeV/c	51 GeV/c	635 GeV/c
$\langle p_B \rangle$	118 GeV/c	22 GeV/c	43 GeV/c	445 GeV/c
$\langle p_\mu \rangle$	32 GeV/c	13 GeV/c	36 GeV/c	280 GeV/c
Median L	8mm	1.5mm	3mm	42mm
Mean L	16mm	4.7mm	13mm	95mm

* Present luminosity $\approx 10^{30}$ cm^2 s^{-1} for the Fermilab Collider. Presuming injector upgrades and corresponding detector upgrades to take advantage of the higher luminosity, this may be increased to 10^{31} cm^2 s^{-1} in the next few years.

** 10^7 interactions per second is taken as a limit for a high rate 4π B physics collider detector to avoid the problem of multiple high multiplicity events per bucket.

*** Taking into account the atomic number enhancement of the heavy flavor cross sections in heavy targets relative to the total cross section.

together with the long B decay paths (average ≈ 95 mm) give the SFT the unique capability of directly observing the B track itself. For a vertex detector like the one described for the SFT spectrometer of EOI-14 (plus subsequent modifications suggested to the SSC PAC[*]), an average B produced in a 20 TeV fixed target interaction would pass through 30 planes of silicon before decaying. This allows the charge of the B to be determined from direct observation of the B hadron, leading to significant advantages in particle-antiparticle tagging (using $B^{\pm}_u$ tagging).

The features of B production in a 20 TeV fixed target experiment are summarized in Table I below and contrasted with other fixed target and collider opportunities.

In summary, the simplicity of the microvertex detector together with the relative cleanliness of the events (the average charged multiplicity at 193 GeV is estimated to be approximately 20), and the high momentum and long decay paths lead to good efficiencies for detecting, tagging and reconstructing large numbers of particular exclusive B decay chains. In addition, these factors lead to relative effective triggers such as the single and dimuon triggers discussed below. The decay chain, $B^0_d \to \Psi K^0_s$ with the subsequent decays of the $\Psi \to \mu\mu$ and $K^0_s \to \pi^+\pi^-$, tagged by a $B^{\pm}_u$ whose charge has been determined by a combination of direct observation and reconstruction of all charged decay products, will be analyzed below as a particular example to illustrate the effectiveness of the SFT.

III. 20 TeV Crystal Channeled Extracted Beam at the SSC

One of the central tenets of the Super Fixed Target B Facility is that it run concurrently and in a non interfering way with the SSC collider program. Extraction by crystal channeling [1,7,8,9] of a relatively low intensity (10^8 protons/sec) 20 TeV proton beam, adequate for the purposes of B physics experimentation in the SFT, meets this criterion as well as several other criteria that must be satisfied by an SSC extraction system. Some of the design criteria imposed on the crystal extraction system are:

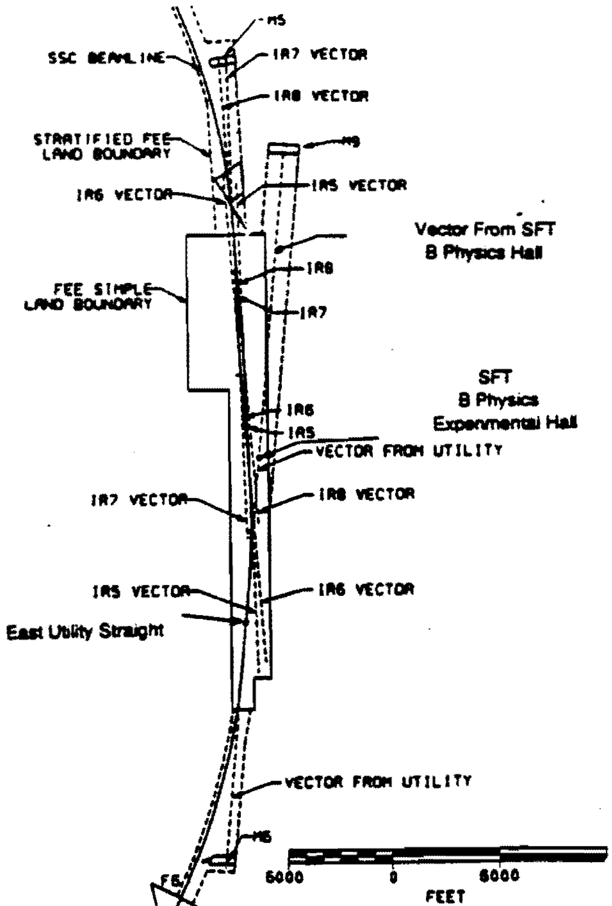
1. No greater need for protons than a "typical" high luminosity interaction region. Proton economics dictate that the facility require no more beam than a high luminosity region, i.e. a few x 10^8 protons per second. Since the SFT facility needs only 2×10^8 protons per second on its silicon microvertex detector/live target (total thickness 0.053 λ_0, 0.26 X_0) to produce the requisite operating rate of approximately 10^7 interactions per second, the constraint of proton economics is met.

2. Non interference with the main circulating beam. The use of a bent crystal placed relatively far from the circulating beam automatically insures minimal interference with the primary beam. The design of a system to feed beam to that crystal without interfering with the circulating beam in any way offers considerably greater challenge, but the differential heating of the high momentum tails of the beam by RF noise as described below offers a solution that makes minimal impact on the bulk of the SSC beam.

3. Non interference with the collider experiments. The crystal channeling extraction system because of high efficiency for channeling with a relatively short crystal should generate only a few x 10^6 interactions per second in the process of extracting 1->2 x 10^8 protons/sec. This is to be compared with the 10^8 interactions per second generated by a high luminosity collider interaction point at a luminosity of 10^{33} cm^{-2}sec^{-1}.

The location planned for the crystal channeling extraction system is in the East Utility straight section, south of the East Campus footprint area. As shown in Fig. 3, the vector from the extraction system passes through the footprint area, and the SFT B physics experimental hall is completely contained in the present fee-simple boundary. Additional underground land rights extending out to M9 have been included in the package to accommodate the muon flux from the extracted beam interactions[10].

There are four major considerations in the design of this extraction system. The first aspect of the extraction system is achieving the



EAST CAMPUS SITTING OF
20 TEV SUPER FIXED TARGET B PHYSICS FACILITY (SFT)

Fig. 3. the SFT Extraction System Plan

proper lattice for the circulating beam for the extraction system. The second feature is laying out the relatively simple geometry of Lambertson magnets and bends, shown in Fig. 4 and described below, which establish the central trajectories of the crystal channeled and the circulating beam within the extraction system. The third facet of the extraction system is the efficiency of the 100 μr bent crystal for channeling the 20 TeV proton beam which has an emittance of 1 π mm mr/p (GeV/c). The fourth facet of the extraction system is the method by which protons are fed to the crystal to replenish the phase space swept by the crystal. In what follows, we anticipate that planar channeling is to implemented by a Si crystal bent along the (110) planes with constant curvature.

To implement the SFT extraction technique, a high-dispersion (4 meters), parallel (β_x=360 m, β_y=517 m) lattice must be obtained in the East Utility straight section, south of the East Campus footprint of the SSC. Such a tune of the SSC can be produced according to the calculations of A.Garren[11] without substantial modification of the present SSC lattice design. No magnets are moved relative to the normal lattice configuration, but eight quadrupoles in the dispersion suppression section are run at different currents than that of the normal lattice tune. The dispersion and beta functions in and near the utility straight section are shown in Fig. 5.

Close to the point of maximum dispersion, the circulating beam will be bent by 0.7 mr into a 500 meter dogleg, the apex of which will be formed by a string of Lambertson magnets (see Fig 4). As shown in Fig. 4a, a 3 cm long bent silicon crystal is placed just downstream of the 0.7 mr bend. This crystal is positioned 1 mm from the central trajectory in the tail of the beam (which by virtue of being at a high dispersion point is the far off momentum tail of the beam) as shown in detail A of Fig 4c.

The bend of the crystal is set to 100 μrad in the planned geometry of the extraction channel to direct the 20 TeV beam into the field free hole in the Lambertson magnet string. Because of the large distances available at the SSC, this rather small bend can be chosen for the SFT extraction system. As we will see below, this small bend will enhance the efficiency of channeling when bending dechanneling effects are considered. As shown in Fig. 4, Detail B, 20 TeV protons impacting on the crystal are bent away from the circulating beam by 100 μr and gradually separate from the main beam until 250 meters downstream they pass through a field free channel in the iron yoke of the Lambertson magnet string and drift 3000 meters to the SFT experimental area. The main beam is deflected at the Lambertson magnet string back into the "normal channel".

The third facet of the extraction system, the efficiency of extraction of the 20 TeV protons can be be affected by several dechanneling phenomena. Dechanneling can take place due to Coulomb multiple scattering, to proton angles too large with respect to the crystal lattice

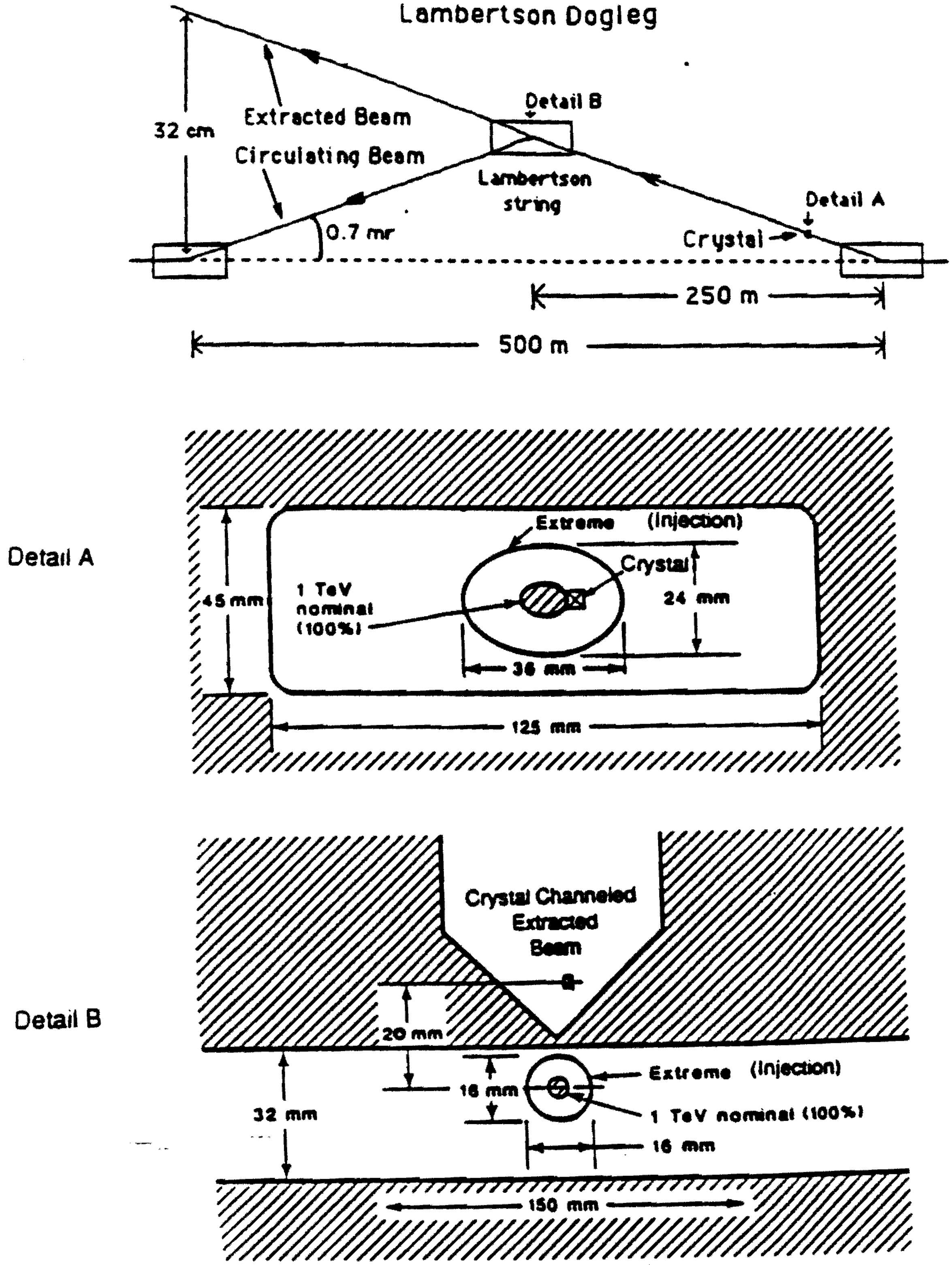


Fig. 4. Lambertson Magnet Dogleg and Channeling Crystal Configuration for the SFT Extraction System

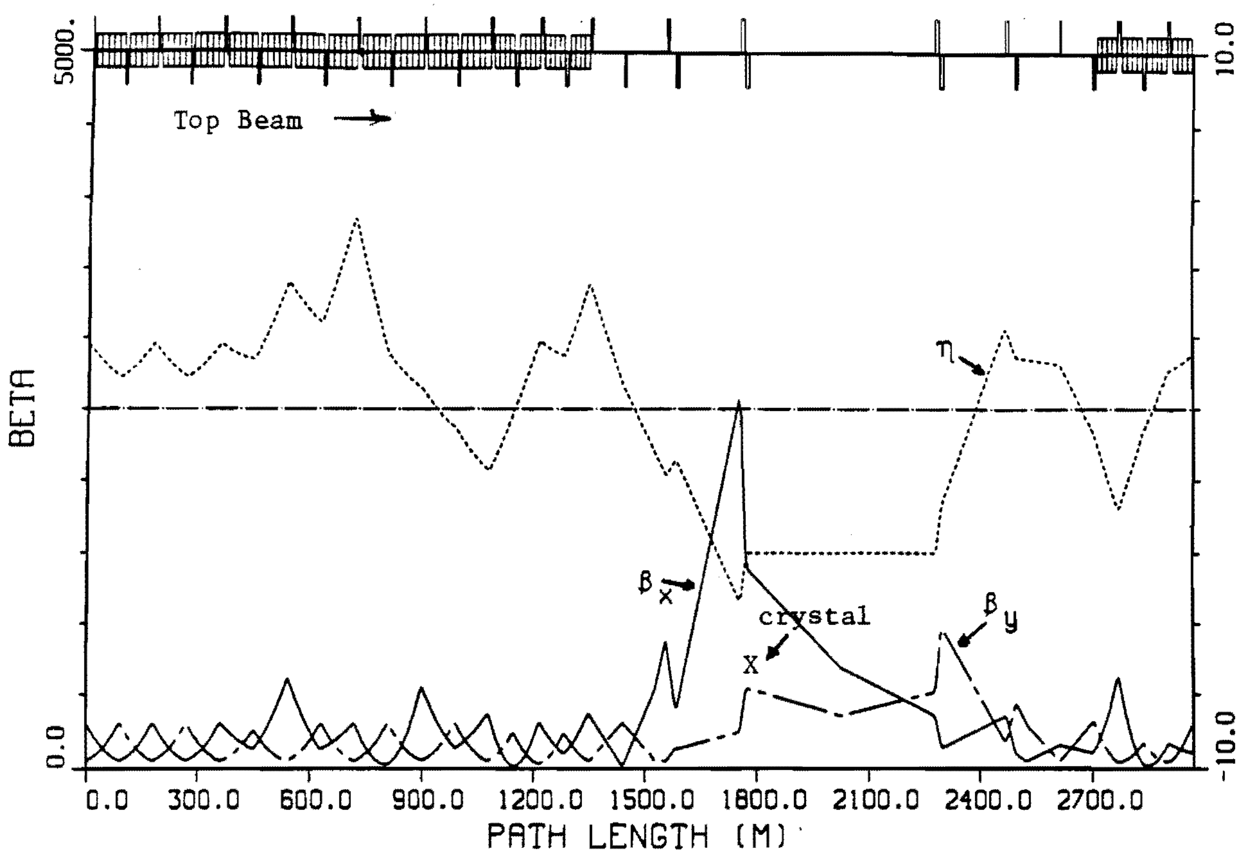


Fig. 5. The dispersion (eta) and beta functions for Garren's modified lattice for the East utility straight section.

planes, to bending dechanneling (i.e. cases in which the coherent electromagnetic force exerted by the crystal lattice fails to bend a given proton through the prescribed channel), and to surface acceptance losses (the losses that occur when the incident proton encounters an atomic scattering center and fails to be inserted properly into the interstitial gaps between crystal planes).

The first of these possible dechanneling mechanisms is negligible at SSC energies because of the negligible Coulomb multiple scattering of a 20 TeV proton. The angular acceptance of the crystal for the 20 TeV protons is also good since the emittance of the beam (and hence the angular spread of the beam) is quite small. The rms angle of a proton, because of the parallel optics at the crystal, is 0.3 μr, well within the critical angle of 1 μr for the crystal. We estimate dechanneling of less than 1% due to this effect.

The bending dechanneling depends to a large degree only on the ratio of momentum of the beam to the bending radius of the crystal. This ratio is 0.67 cm^{-1} GeV/c for the proposed deflection by 100 μradians of the 20 TeV beam by the 3 cm crystal in the SFT extraction system. The value of this ratio for the SFT facility is close to that of several channeling experiments done with Si(1,1,1) planes at lower energies with smaller bend radii[12]. The rough agreement of these experiments with the theoretical predictions gives us confidence that we can use the theoretical calculations for the bending dechanneling in the (1,1,0) case, which are shown in Fig. 6. From the upper curve of Fig. 6, we estimate the bending dechanneling loss to be approximately 17% for the SFT extraction configuration.

The final dechanneling mechanism, surface acceptance, is estimated by using the rms amplitude of the thermal vibration of the

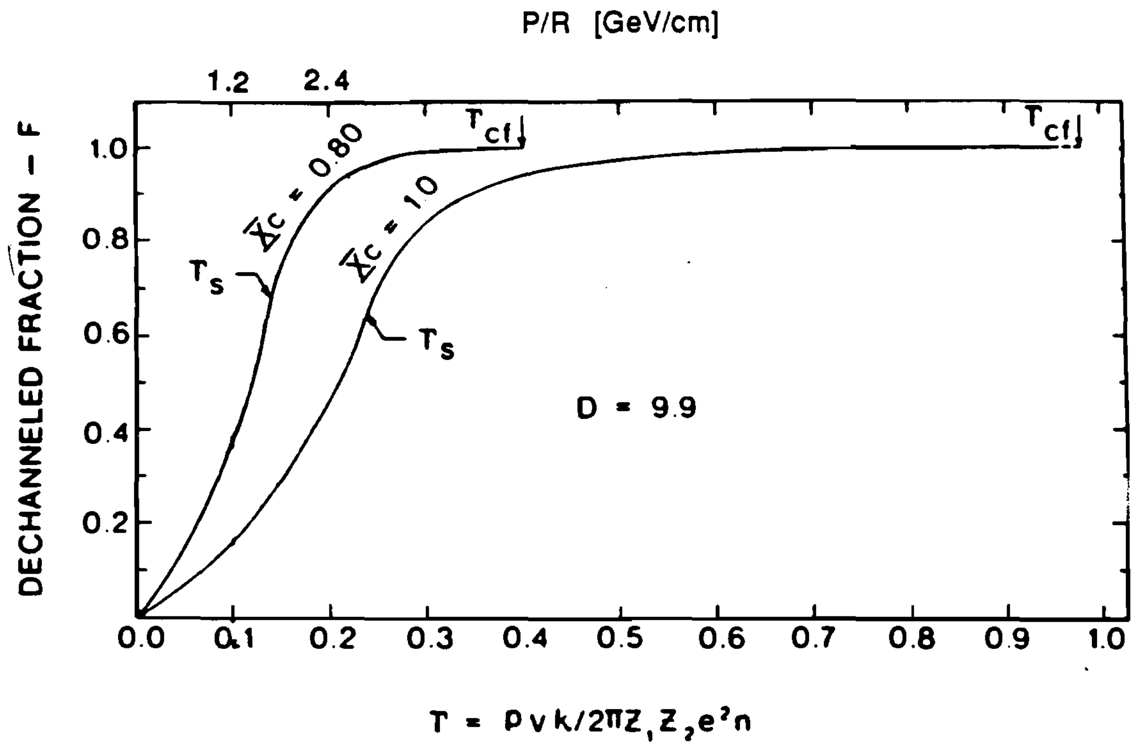


Fig. 6. Bending dechanneling predicted for Si (1,1,0) planes as a function of p/R, from Ref. 12. The upper curve corresponds to dechanneling at the Thomas-Fermi screening distance from the atomic planes.

silicon atom to define a region surrounding each atom in which the incident protons will undergo surface dechanneling. The magnitude of the surface dechanneling is of order 20%, taking the thickness of the excluded region to be 0.19 angstroms, which is very nearly the same as the Thomas-Fermi screening distance.

Taking all the dechanneling effects into account we obtain a first pass channeling probability to be 66%. Of course, not all protons that are not channeled on the first pass are lost. The dechanneled protons will have a chance on subsequent passes to undergo channeling. We estimate the composite multipass channeling probability to be 80%. Those protons that are not channeled have a few percent probability of undergoing a nuclear interaction in the 0.067 λ_0 silicon crystal. The nuclear interaction will lead to a few x 10^6 interactions/sec from the crystal that must be cleaned up by downstream collimation and bending systems. At present, we do not anticipate that these interactions would cause any difficulty for the high p_t interaction regions on the west side of the SSC, a complete arc away.

More sophisticated calculations have been carried out by A. Taratin[13] to verify and improve on the simple estimates of the efficiency of the SFT extraction system discussed above. In the calculations, individual particles from the SSC emittance were tracked through the crystal. Correlations between individual sources of losses (such as the increase of the width of the thermal vibration layer decreasing both the surface acceptance and the bending dechanneling in concert) have been taken into account. To perform this more sophisticated analysis, the equations of motion for a particle in the effective potential of the crystal were solved, and Coulomb multiple scattering and nuclear scattering were included in the Monte Carlo simulation.

The result of this work indicates that the simple estimates initially performed for the SFT EOI underestimated the efficiency of the extraction process. The SFT single-turn extraction efficiency for a 3 cm long crystal is found to be 80%, for a crystal which is perfectly aligned and has a perfectly flat surface on the edge parallel to the beam (i.e., zero "septum width"). Multi-turn extraction efficiency was also calculated in the same simulation. Particles were counted as "extracted" if their upward bend angle exceeded 99 μradians (the bend angle minus the critical angle) at the exit from the crystal, available for another chance to be channeled on the next turn if their vertical angle was less than 25 μradians, and lost to the wall of the vacuum chamber for angles between 25 and 99 μradians. The result was that multiturn extraction efficiency for particles incident on the face of the crystal was estimated to be 93%.

These more complete calculations indicate that total losses are minimized for both single-turn and multi-turn extraction for crystal bend radii between 300 and 500 m, corresponding to crystal lengths between 3 and 5 cm. The reason for a minimum is that, as the crystal is lengthened, bending dechanneling losses decrease, but nuclear and coulomb scattering losses of dechanneled particles increases.

The other facet of the extraction system is development of a system to refresh the high momentum tail phase space swept by the crystal. The mechanisms for populating these tails have at least two natural components, beam gas scattering and the high p_t interaction regions themselves. These mechanisms produce sizable excursion from the central trajectory at the 10^7 proton/sec level[14]. However, a more positive control over the magnitude of these tails and the refreshing mechanism is desirable. The technique under study to produce off momentum protons is the introduction of RF noise in specific frequency ranges into the RF system. This RF noise when introduced at the right frequencies heats the high momentum tails of the beam preferentially. The purpose of this "differential" heating of the beam is to cause slow diffusion of 10^8 protons/sec from the central region of the beam into the momentum tails such that the net displacement of the protons at the high dispersion point on each betatron oscillation becomes larger the further off momentum the proton is driven. On the final betatron oscillation on which the proton is inserted into the crystal channel, the step size must be larger than the effective septum width of the crystal.

Present results suggest that phase or amplitude noise injected into the RF system at frequencies near the synchrotron frequency of the SSC will produce a diffusion rate of approximately 10^8 protons/sec with an average final step size (on the step in which the proton is inserted into the crystal) greater than one micron. Because the bend of the crystal is out of the plane of the orbit of the SSC beam, the effective septum width of the crystal is set by the flatness of the surface adjacent to the beam rather than the relation of the crystal lattice to the beam. Since the crystal can be polished to better than a tenth of a micron by conventional lens techniques, a step size of one micron is quite adequate for purposes of channeling. The alignment of the crystal surface with respect to the beam is still a concern but it is estimated that this can be accomplished adequately by an empirical process involving a combination of steering of the beam and positioning of the crystal.

To date, three forms of RF modulation have been considered for production off momentum tails of the SSC beam of the desired intensity: phase noise, amplitude modulation at specific frequencies, and adding a small-amplitude signal at a higher harmonic of the fundamental RF frequency.

Phase noise has been studied in the greatest detail. H. Brown as part of this study has performed a simple Monte Carlo simulation using random flat phase noise of maximum value ±0.01 rads. With injection of this sort of RF noise, the final rms step size (hereafter called x_h) for a particle first penetrating into the crystal was 2.5 microns. However, the extraction rate was 10^{-2} sec^{-1} of the circulating beam, which was much too fast: since the circulating beam will contain 10^{14} protons at $L=10^{33}$ $cm^{-2}sec^{-1}$, the desired extraction rate of 10^8 protons/sec corresponds to a fractional extraction rate of 10^{-6} sec^{-1}. Furthermore, for this study the crystal was placed 0.15 mm from the horizontal center of the circulating beam, an unconservative configuration.

Newberger and Shih[18] continued this approach in more detail, and compared the results with the analytical work of Dome[19]. They find that "white" phase noise with a Gaussian distribution of amplitudes as a function of the Gaussian width, σ_ϕ. For σ_ϕ = 0.155 rads produces an extraction rate of about 10^{-3} (again, too high), and an average x_h of about 5 microns. In addition, the "white" phase noise almost doubled the rms bunch length of the RF bunch before particles hit the crystal, an effect which causes an unacceptable decrease in collider luminosity. The white noise heats the entire beam, not just the low-intensity edge of the RF bucket. In the study, the crystal was placed 1 mm from the center of the circulating beam. With a dispersion of 4 m at the crystal location, 1 mm corresponds to a dP/P at the edge (the separatrix) of the RF bucket of 2.5×10^{-4}.

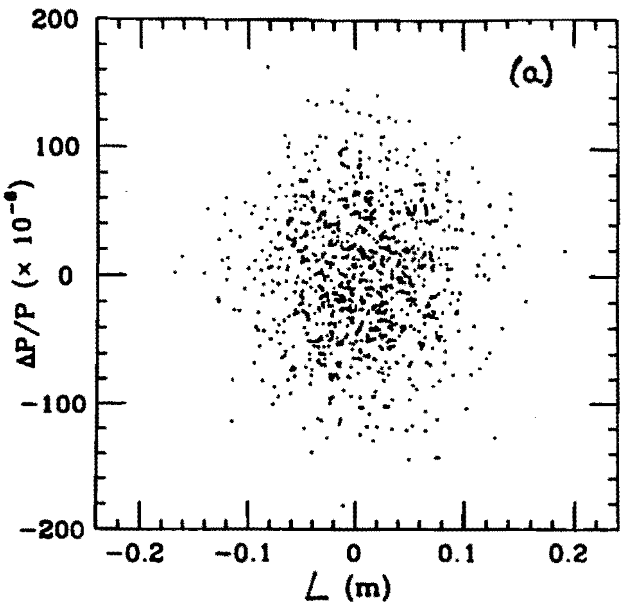
To achieve proper differential heating of the tails of the beam relative to the core, Shih and Taratin[13] have studied injecting filtered RF phase noise, using the same Monte Carlo program used to study the "white" RF noise effects. In this study, RF noise was filtered to admit only frequencies less than 0.85 times the synchrotron frequency. An small extrapolation of the filtered noise result indicates the desired fractional extraction rate of 10^{-6} sec^{-1} can be achieved for a σ_ϕ of 0.004 rads, and the rms x_h was 1.0 microns. More importantly, the particles which hit the crystal face came from the edges of the RF bucket, and the size of the high-density core was not noticeably lengthened. The results are illustrated in Figs. 7 a, b, and c, which show scatterplots of dP/P vs. the longitudinal position in the bunch for the original beam, the final circulating beam after 10^6 turns, and the original position in the bucket of those protons which hit the crystal. In short, the filtered RF noise solution shows great promise.

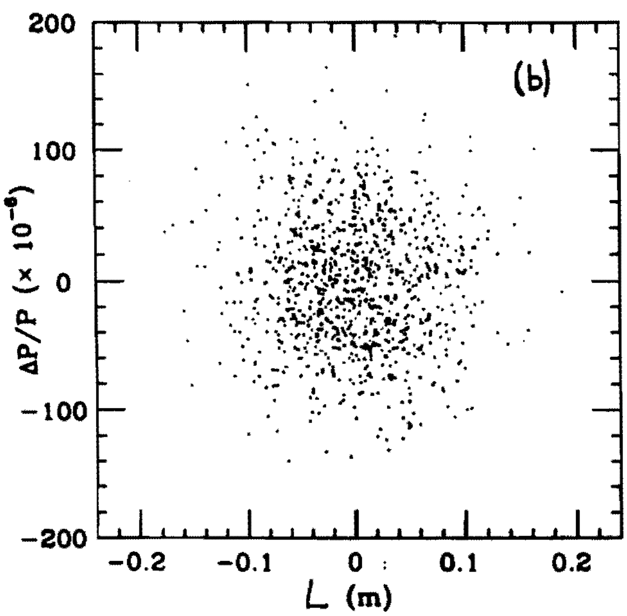
Other promising approaches are being investigated currently. A variant of the filtered phase noise labeled "notched noise" is being studied by Newberger and Shih. Noise in the frequency range of the revolution frequency and above is added to the band of noise at less than the synchrotron frequency. This higher band serves to diffuse particles slowly from the central core out to the region where the low-frequency band is most effective. Preliminary results indicate a relatively uniform extraction rate.

A third approach, amplitude modulation of the RF voltage at discrete frequencies, is being investigated by S. Peggs and, separately, by B. Norum. Amplitude modulation has the advantage that it has the greatest effect on particles part way between the center of the bucket and the separatrix, and no effect on particles at the center. For example, a 2% amplitude modulation at 1.5 times the synchrotron frequency has been shown to create a strong "island" in the Poincare plot of the bucket space (see Fig. 8), powerful enough to step particles quickly over the crystal septum which is near the separatrix. This study is not yet complete but results obtained thus far are quite encouraging.

B. Norum in a second approach to the introduction of RF amplitude noise has advanced the idea of introducing a weak RF cavity operating at certain higher harmonics of the fundamental RF frequency. Because only every sixth RF bucket of the SSC will contain protons, the weak RF cavity will not disturb the core of the filled buckets. The higher harmonic need only come back in phase with the fundamental RF six buckets later. The amplitude of the fundamental RF can be decreased slightly so that the sum of the fundamental RF and the higher-harmonic match the original RF not only at the center of the bucket, but for the distance along the length of the bucket for which the sine-wave RF can be considered linear. The core of the beam is affected even less than with the amplitude modulation discussed above. This approach also looks promising.

The existence of several feasible techniques which offer orthogonal methods of achieving a smooth, non-disruptive extraction process, is very encouraging. All of the above ideas can be investigated experimentally at existing machines such as the Fermilab collider, and definition of a set of beam tests is underway.





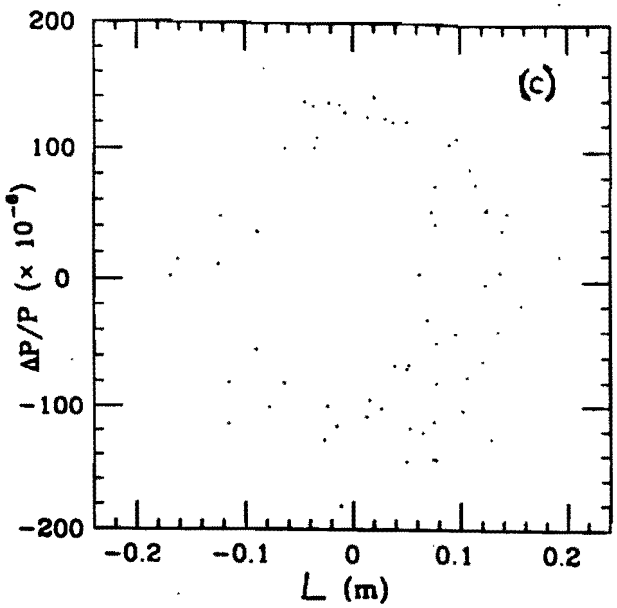


Fig. 7. Longitudinal phase space distributions for beam perturbed by filtered phase noise. L is the distance along the beam from the center of the bucket. (a) Original distribution before noise is introduced. (b) Distribution of circulating beam after 10^6 turns with filtered noise of amplitude σ_Φ =0.015 rads. (c) Original distribution of those particles which hit the crystal after 10^7 turns.

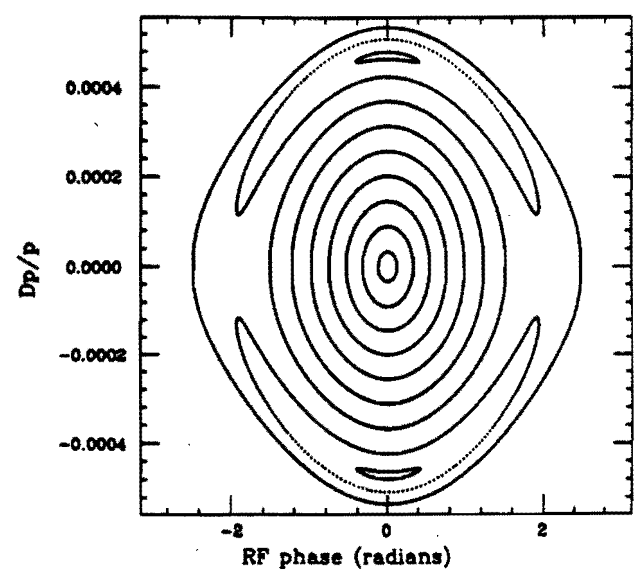


Fig. 8. Poincare plot, showing islands developed as the result of amplitude modulation of frequency 1.5 times the synchrotron frequency.

IV. the SFT Spectrometer

The SFT spectrometer shown below in Fig.9 is a two magnet forward spectrometer.

At present, the strategy for the SFT magnetic system is to run M1 and M2 with equal and opposite polarities to preserve projectivity to the target in both planes behind the magnets and to simplify triggers which depend on tracking charged particles (for example, muons) in the spectrometer tracking system. The solid angle coverage, as already mentioned, is from 3 mr to 75 mr for all charged particles and photons. The length of the spectrometer is approximately 75 meters, approximately three times as long as the comparable Fermilab spectrometer to compensate for the factor of three decrease in average angle of the secondaries between $\sqrt{s}$ = 38.7 GeV and 193 GeV pN interactions.

The spectrometer tracking is arranged so that more finely grained charged particle detectors are used closer to the beam. The outer part of the solid angle is covered by straw tubes and trigger pad chambers of the sort under construction at Fermilab for experiment E771. The small inner chambers are presently planned to be microstrip proportional chambers. Details of this chamber arrangement can be found in EOI-14.

No hadron calorimetry is contemplated for this detector at the present time since the main objective of the detector requires the reconstruction of the majority of the tracks, and the triggers that have been under discussion thus far do not require a hadron calorimeter. Instead, the main calorimetry consists of a very high resolution electromagnetic calorimeter which will contribute to the reconstruction of B final states containing π^0's. This device can be designed and unconstrained by the necessity of maintaining compensation with a hadronic section. The main body of the calorimeter is presently planned to be scintillating fiber embedded in a Pb matrix, although heavy crystals are still being considered. The preconverter for the electromagnetic detector is presently considered to be either a silicon pad structure embedded in a Pb or tungsten plate array or a scintillator pad structure. The goal for electromagnetic resolution is $2\%+9\%/\sqrt{E}$.

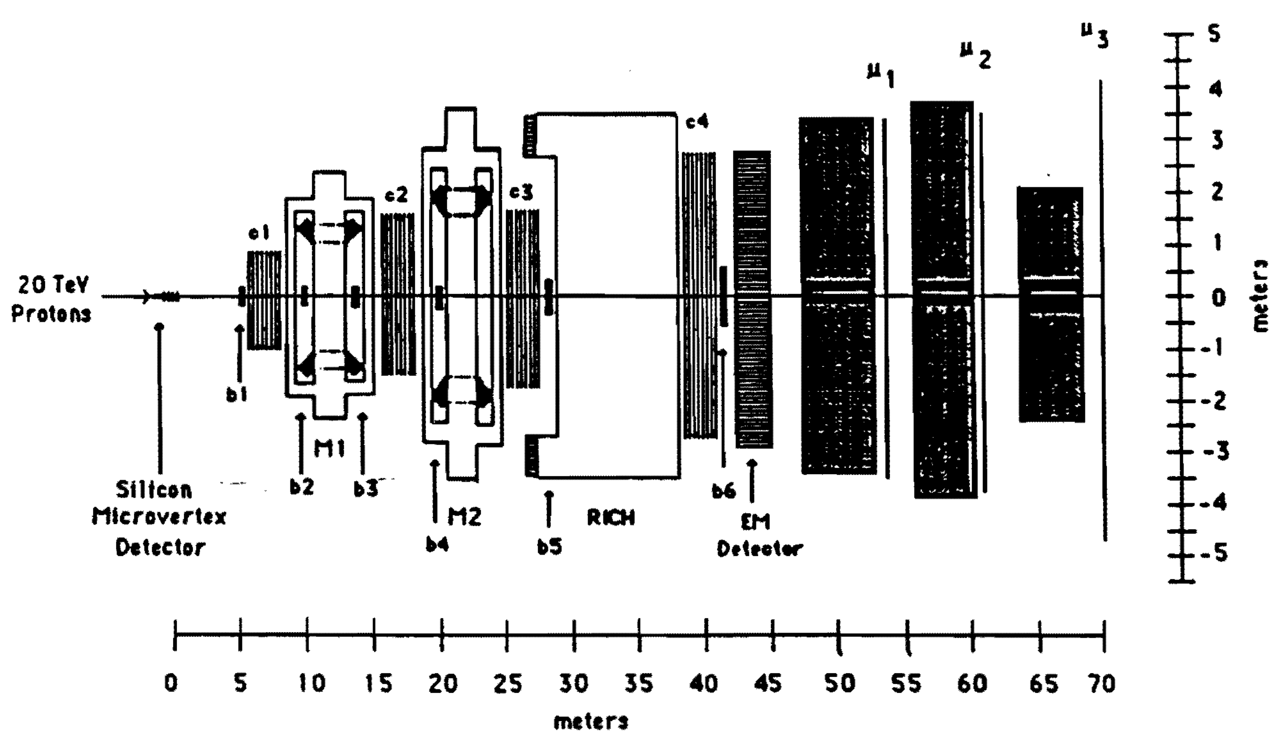


Fig. 9. The SFT Spectrometer

The microvertex detector is composed of 120 planes of 200 micron thick, double sided silicon strip detectors. In addition, a few silicon pixel planes will be included to aid pattern recognition. The vertex detector is divided longitudinally into two sections; a live target section composed of 90 5x5 cm^2 planes spaced by 2 mm and a tracking section composed of 30 10x10 cm^2 planes with 2 cm spacing. Interactions occur in the material of the silicon planes. An average B produced in the tightly spaced live target region will pass through many planes (average decay length $\approx$ 95 mm) before decaying. Thus, with this configuration of microvertex detector, it is uniquely possible for the SFT (in distinction to other B physics experimental configurations) to directly observe the B tracks themselves. This makes it possible to determine the charge of the B unambiguously over an estimated 50% of the B decays. This will greatly aid the tagging of various B decays by the determination that the "other" B in the event is a B_u. In addition, the detection of doubly charged heavy flavor states becomes possible by direct observation of the heavy flavor track if ADC's are put on the silicon detector.

Radiation damage in the silicon detector is caused by the beam and secondaries from the interactions. Since the average multiplicity of the interactions is approximately 20 and the number of non interacting beam particles is also 20 (0.053 λ_0 target thickness), radiation damage is approximately equal due to both sources and no worse at SSC energies than at Fermilab energies. Either a large beam spot or periodically moving the vertex detector transverse to the beam will be used to evenly distribute radiation damage.

At present at least two kinds of triggers are planned for the SFT. Single and dimuon triggers and secondary vertex triggers will be incorporated into the overall scheme. The implementation of these triggers uses Programmable Array Logic technology at Level I, associative memories at Level II and microprocessor based electronics at Level III to accomplish a reduction from the basic interaction rate of 10^7/sec to the data logging rate of 10^3 events/sec as described in EOI-14. The effectiveness of the these triggers is discussed below.

V. B Physics In the SFT

The beam and spectrometer of the Super Fixed Target B Facility described above provide an excellent means of studying rare B decays and measuring CP violation in the B system. As a first step in the evaluation of the SFT capabilities for detecting and triggering on, for tagging, and finally, for completely reconstructing particular B decay modes to extract physics, estimates have been made of the expected signal to background ratio of two different trigger samples (single and dimuon triggers), at each level of the trigger and offline analysis, and the yields of $B \to \mu$ and $B \to J/\Psi \to \mu\mu$ inclusive modes per year have been estimated.

In the case of the $B \to \mu$ mode, a sample of events is obtained which is rich in B decays and in which the other B in the event is "tagged" by the charge of the decaying muon. For the $B \to J/\Psi \to \mu\mu$ decays, the ensemble of J/Ψ modes selected is especially interesting (as can be seen from the unitarity triangle of Fig. 1) for their potential for CP violating asymmetries. These $B \to J/\Psi$ decays can be "tagged" either by an accompanying $B \to \mu$ decay or by observation of an accompanying $B^{\pm}_u$ decay. In either case, the ability to directly observe the B track will aid in making the "tagging" process more certain. Both of these inclusive modes produce high p_t muons (see Fig. 10a,b) which aid in triggering and offline separation of the B's from backgrounds (Fig. 10c,d).

V.A The $B \to \mu + x$ Data Sample

Approximately 23% of all $B\overline{B}$ events will produce at least one muon via the semileptonic decay modes. The large branching ratio and the large production cross section for beauty at the SFT lead to a large ratio (between $1/3.2 \times 10^4$ to $1/8.2 \times 10^3$) of $B \to \mu + x$ events produced per interaction. Furthermore, the relatively large p_t of the muons from the semimuonic decays and the fact that the B events should have secondary vertices make possible powerful triggers (see EOI-14) and very significant increases in the enrichment factors for the events that are written to tape. Indeed, 50% of the B decays have muons with p_t >1.5 GeV/c (the threshold of the SFT muon p_t trigger) at $\sqrt{s}$= 193 GeV/c

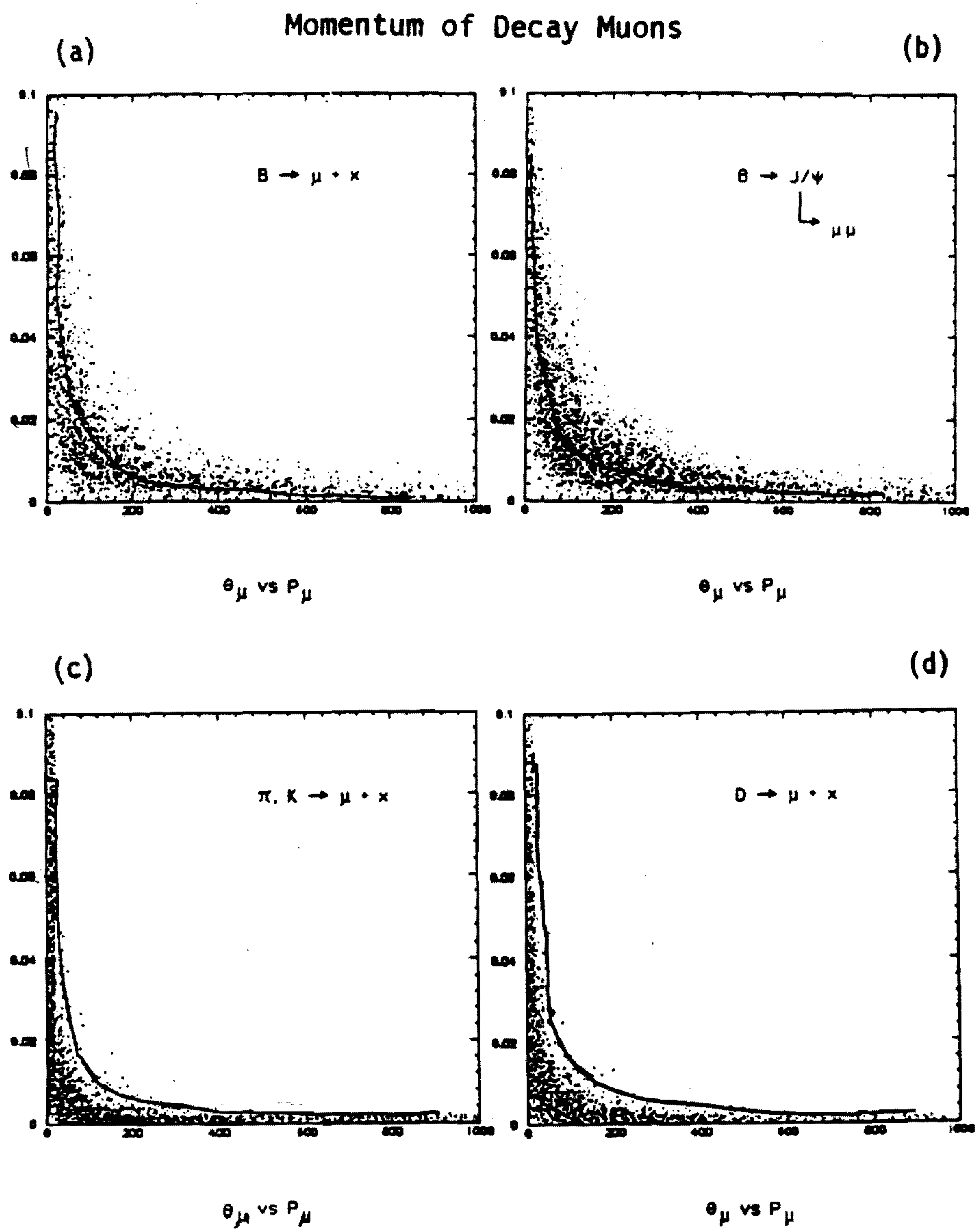


Fig. 10. Laboratory Momentum of Decay Muons vs Laboratory angle for:
a) B->J/Ψ->μμ: b)B->μ semileptonic; c) K, ->μ semileptonic;
d) Charm->μ semileptonic

(See Fig, 10; the superimposed curve is the contour of p_t=1.5 GeV/c). It is estimated that trigger selectivity in the SFT will produce one B->μ decay event for every 5 to 20 triggers written to tape.

In the offline analysis, according to Monte Carlo studies, the requirement of a 30 micron impact parameter for the muon in the SFT silicon microvertex detector improves the signal to background by a factor of approximately 10, producing a ratio between 2/1 and 1/2 for the events surviving the first step of the offline analysis while retaining the majority of the signal (greater than 90%). Requiring the presence of additional charged tracks from the secondary vertex will further help to eliminate fake B->μ candidates due to K, π->μ decay which appear not to originate at the primary vertex because of μ mismeasurements. The detection of additional tracks from the secondary vertex reduces the backgrounds by another factor greater than ten leading to a signal to background ratio in the resulting data sample between 5 and 20 to 1.

V.B B->J/Ψ->μμ Data Sample

Because of the cumulative branching ratios, the fraction of dimuon triggers due to actual B ->J/Ψ->μμ decays is relatively small. Given the 1.1% branching ratio for B-> J/Ψ + anything and the 6.9% branching ratio for J/Ψ->μμ, only 1.5×10^{-3} of the BB events will contain a decay of this type (taking into account that there are two B's in every event). Therefore, only one event out of between 1.3 to 5.1×10^{6} interactions will have a B->J/Ψ->μμ decay.

However, the backgrounds to the B->J/Ψ ->μμ events will be quite small and can be reduced more easily in the trigger and the offline analysis than the backgrounds to the B ->μ+x events. The requirement for the dimuon to be a J/Ψ, by itself, eliminates a large portion of the background decay dimuons. The portion of J/Ψ production at 20 TeV/c not due to B decay in the Si live target of the SFT detector is estimated to be approximately 6 μb (extrapolating the lower energy J/Ψ production cross sections using the technique of L. Lyon[17] and using an A dependence of $A^{0.93}$). The $B\bar{B}$ beauty hadron production cross section in 20 TeV/c interactions is estimated to be between approximately 30 to 120 μb for the material in the target section, assuming a linear A dependence of the beauty production cross sections and using the third order beauty hadroproduction cross section calculations of K. Ellis et. al mentioned above. Using a branching ratio for B->J/Ψ of 1.1 %, between 1/18 and 1/5 of the J/Ψ's produced at $\sqrt{s}$=193 GeV are due to a $B\bar{B}$ events in which one or the other of the B's decays via a J/Ψ decay mode. Therefore, the major objective of the online trigger and the offline analysis will be to select events containing J/Ψ->μμ decays.

The SFT dimuon trigger will immediately produce a significant enrichment of the signal to background ratio. For the SFT, between 1/40 to 1/150 dimuon triggers written on tape will be due to B->J/Ψ->μμ. As the first step in the offline reconstruction, a crude dimuon mass requirement will further increase this enrichment to a level greater than that expected naively from the ratio of B-> J/Ψ to the direct J/Ψ production cross sections, since the presence of secondary vertices in the events in the Level II trigger(which will tend to suppress the direct J/Ψ production) has already been crudely required. Even ignoring this suppression, a ratio 1/3 to 1/12 signal to background (or better) is expected after the first step of the offline analysis with almost all the signal retained. This ratio should become much greater than 10/1 after the second step in the offline analysis, the requirement that the muon pair come from a secondary vertex.

In Table II below, we summarize the enrichment factors that we expect to achieve from the trigger strategies and the offline analysis steps.

V.C Yields of B->J/Ψ and B->μ Inclusive B Decays in the SFT

Assuming that 10^7 seconds of operation at 10^7 interactions per second represents a standard year of operation, 10^{14} interactions will take place in the SFT per year. Using Table I, between 1/1900 and 1/7700 of all $\sqrt{s}$ = 193 GeV interactions in the SFT microvertex detector target section will contain B's and, therefore, 1.3×10^{10} to 5.2×10^{10} $B\bar{B}$ events will be produced per year. Taking into account

Table II

Beauty Enrichment Factors at Various Levels

Step	DiMuon Trigger (signal = B->J/Ψ->μμ)	Single Muon Trigger (signal = B->μ +x)
BB/interaction	$1/7.7\times10^3$->$1/1.9\times10^3$	$1/7.7\times10^3$->$1/1.9\times10^3$
Produced signal/int	$1/5.1\times10^6$->$1/1.3\times10^6$	$1/3.2\times10^4$->$1/8.2\times10^3$
Accepted signal/ Level I	$1/8.1\times10^2$->$1/2.0\times10^2$	$1/2.1\times10^2$->$1/5.3\times10^1$
Signal/Level I* Level II	1/150->1/40*	1/20->1/5*
Offline Step I Sig./backgrd	1/18->1/5	1/2->2/1
Offline Step II Sig./backgrd	>>10/1	5/1->20/1

*This is the enrichment factor for events written to tape.

branching ratios, between 2.0×10^7 and 7.8×10^7 B-> J/Ψ->μμ and 3.1×10^9 to 1.3×10^{10} B->μ+x decays take place per year of operation. Of these, 6.7×10^6 to 2.6×10^7 B-> J/Ψ-> μμ and 5.6×10^8 to 2.2×10^9 B->μ inclusive decays are expected to survive the SFT trigger and the early stages of the offline analysis.

V.D Sensitivity of the SFT to CP Violation in the Exclusive Mode B->J/ΨK^0_S

Since the measurement of CP violation is perhaps the ultimate test of a B physics experiment or strategy, requiring the largest sample of reconstructed B's, the capabilities of the SFT for performing this task should be evaluated as a measure of the power of the fixed target option. As a particular example of the ability of the SFT to make measurements of CP violation, the decay B^0->J/Ψ K^0_S has been examined. This is only one of many different exclusive modes that can be investigated. As mentioned above, this mode is an example of the generic B->f decays where f is a CP eigenstate (CP$\overline{\langle f\rangle}$ = ±<f>). In the case of this mode, if there is CP violation (λ≠0), the task will be to distinguish between time distributions of the form

$$e^{-\tau}(1\pm\lambda\sin\Delta m\tau/\gamma)$$

where the ± refers to whether the parent B was a B or $\overline{B}$ and where τ is measured in units of B lifetime, γ. Integrating this time distribution over one half period of an oscillation $\tau=\pi\gamma/\Delta m$, a difference in the number of events is observed for B and $\overline{B}$ decays, ΔN, which is proportional to the integral of the differences of these time distributions.

$$\Delta N = N-\overline{N} \approx 2\lambda \cdot \int_0^{\gamma\pi/\Delta m} \{e^{-\tau}\sin(\Delta m\tau/\gamma)\}\, d\tau$$

$$= 2\lambda\{1+e^{-\pi\gamma/\Delta m}\}\cdot \{\Delta m/\gamma\}/\{1+(\Delta m/\gamma)^2\}$$

In the same way, the sum of N and $\overline{N}$ distributions can be obtained.

$$N_T = N+\overline{N} \approx 2\cdot\int_0^{\gamma\pi/\Delta m} e^{-\tau}\, d\tau$$

$$= 2\cdot(1-e^{-\gamma\pi/\Delta m})$$

The asymmetry (for one half oscillation) between B and $\overline{B}$ is defined as the ratio

$$A = \Delta N/N_T$$

$$= \lambda\{(\Delta m/\gamma)/(1+(\Delta m/\gamma)^2)\}\cdot \{(1+e^{-\gamma\pi/\Delta m})/(1-e^{-\gamma\pi/\Delta m})\}$$

Using the value of $\Delta m/\gamma = 0.78$ obtained by the Argus collaboration[18] for B_d, the expected asymmetry can be written as

$$A \approx 0.5\lambda$$

for the first half period of the oscillation. For B_s decays into CP eigenstates (assuming that $\Delta m/\gamma$ for Bs is approximately 1/5 of $\Delta m/\gamma$ for B_s),

$$A \approx 0.6\ \lambda$$

In order to measure these asymmetries with a statistical significance of a given number of standard deviations, a large number of B decays must be reconstructed and tagged in the exclusive mode under study. It can easily be shown that $N_T \approx (\#\sigma/A)^2$, where $\#\sigma$ is the number of standard deviations of significance desired in the measurement of the asymmetry.

Therefore, $N_T = (3/A)^2 = (6/\lambda)^2$ numbers of B_d plus $\overline{B}_d$ exclusive decays into a CP eigenstate are required to measure a three sigma decay asymmetry between the particles and antiparticles, if measurements are restricted to the first half period of an oscillation. For maximal CP violation ($\lambda=1$, $A=0.5$), $N_T=36$ events. There is, of course, no need to restrict measurements to the first oscillation since the time distributions are well measured in the SFT. For a more reasonable choice of $\lambda=0.3$, $A=0.15$, $N_T=400$ events (200 B's and 200 $\overline{B}$'s) are required. The preceding analysis ignores systematic effects. However, with the time spectra for the particle and antiparticle decays well measured (with resolution of better than 0.05 picosecond), many of the troublesome problems (for example, different rates of production of B and $\overline{B}$'s) that accompany a simple counting CP experiment can be eliminated.

As indicated above, 6.7×10^6 to 2.6×10^7 B $\rightarrow J/\Psi \rightarrow \mu\mu$ inclusive decays are expected to survive the SFT trigger and the early stages of the offline analysis. Assuming a hadronization ratio of 2/2/1 for $B_u/B_d/B_s$, (and neglecting the small fraction of B_c or B baryons), 2.7×10^6 to 1.0×10^7 $B_d \rightarrow J/\Psi \rightarrow \mu\mu$ decays will be recorded in a year of SFT operation.

Using the branching ratio for $B_d \rightarrow J/\Psi K^0_s$ estimated by Dunietz and Rosner[19] of approximately 0.05% (approximately 5% of the total $B \rightarrow J/\Psi$ inclusive mode rate) and a branching ratio for $K^0_s \rightarrow \pi^+\pi^-$ of 69%, between 9.3×10^4 to 3.7×10^5 such decays per year will be obtained, divided approximately equally between B and $\overline{B}$ (modulo CP effects and possible slight differences in production rates of B and $\overline{B}$). After requiring that the K^0_s decay in the first 5 meters of the spectrometer and allowing for the additional geometric acceptances other than the acceptance for the two muons (ie. acceptance for the two pions from the K^0_s decay), 42% of the $B \rightarrow J/\Psi\ K^0_s$ decays are preserved for possible reconstruction. Estimating a single track reconstruction efficiency of 90%, a final number of decays for the CP study of between 2.6×10^4 and 1.0×10^5 $B_d \rightarrow J/\Psi K^0_s \rightarrow \mu\mu\pi\pi$ decays are completely reconstructed.

The tagging of the particle or antiparticle nature of the parent B for the J/Ψ exclusive decays is accomplished by at least partially reconstructing the other B in the event. In approximately 65% of the $B \rightarrow J/\Psi \rightarrow \mu\mu$ events, all the decay products of the other B in the event are in the acceptance of the spectrometer. In making this estimate, a reasonable mixture of decay modes for the "other" B have been considered. Imposing the requirement that all of the charged decay products of the other B be in the acceptance of the spectrometer (not absolutely necessary for a tagging process in which the $B \rightarrow \mu$ semileptonic decays are used), 1.7×10^4 to 6.7×10^4 $B_d \rightarrow J/\Psi K^0_s \rightarrow \mu\mu\pi\pi$ events are obtained. By examining these decays of the "other" B in the event, strategies may be developed that allow an estimate of the probability that the B_d was a particle or an antiparticle at t=0. The least ambiguous tag is the one that utilizes the fact that the "other" B was charged. In this sort of tag, the special feature of the fixed target configuration, i.e. that the B's themselves pass through many planes on average, helps a great deal in the tagging process since the charged or neutral nature of the B's can be determined by direct observation of B's. This information can be used as a check on the assignment of positive or negative charge to the B_u. Because of the good resolution of the SFT and the multiple

Table III

$B^0_d \to J/\Psi\ K^0_s$

$\quad K^0_s \to \pi^+\pi^-$

$\quad J/\Psi \to \mu\mu$

Condition Imposed	Event Sample
$B\bar{B}$ produced	1.3 ->5.2×10^{10}
$B \to J/\Psi \to \mu\mu$ (7.7×10^{-4})	2.0 ->8.0×10^{7}
Trigger Acceptance (.33)	0.66->2.6×10^{7}
Hadronization to B_d (40%)	0.26->1.1×10^{7}
$B_d \to J/\Psi\ K^0_s$ (5% of $B_d \to J/\Psi + x$)	1.4 ->5.6×10^{5}
$K^0_s \to \pi^+\pi^-$ (69%)	1.0 ->4.0×10^{5}
K^0_s Acceptance (42%)	0.42->1.7×10^{5}
$B \to J/\Psi\ K^0_s$ Track Reconstruction (90%/track)	0.28->1.1×10^{5}
"Other" B Decay track Acceptance (65%)	1.8 ->7.2×10^{4}
Hadronization to Bu (40%)	0.7 ->2.8×10^{4}
Determination of Charge of B_u (50%)	0.34->1.4×10^{4}

measurements of every track, a relatively low level of misidentifications of other tracks in the event can be achieved. Having the extra information about the sum of the charges makes the probability of missing tracks or adding tracks negligible. To be in error, two tracks must be added or missed from a given B_u vertex. Mistagging should be small under these conditions. It is estimated that a good tag using B_u decays can be achieved in more than 50% of the B_uB_d events.

Given a hadronization ratio of 2/2/1, there is a 40% probability of having a B_u produced in association with a given B_d decay. Assuming that the charge of the B_u can be determined correctly more than 50% of the time, a data sample of between approximately 3.4×10^3 and 1.4×10^4 $B_d \to J/\Psi K^0_s$ where the $K^0_s \to \pi^+\pi^-$ and the $J/\Psi \to \mu\mu$ and in which the B_d is correctly identified as having been a B or $\bar{B}$ at t=0 by the presence of a properly identified B_u can be obtained. Use of the $B \to \mu$ decays for tagging will further increase this number. Therefore, the statistics of tagged $B \to J/\Psi K^0_s$ events are at least one to two orders of magnitude greater than necessary for detection of a 15% CP asymmetry at the three σ level in this relatively rare exclusive mode alone. The estimate of the level of statistics required for a CP asymmetry measurement in this one particular decay chain agrees with global estimates given elsewhere[2c].

This particular exclusive decay mode is only one of several $B \to J/\Psi$ modes which are accessible using much the same triggering and tagging strategy. In addition, the possibility of retrieving information from the $B^0_{d,s}\bar{B}^0_d$ configuration has been ignored. However, as a lower limit on the information about CP asymmetry that can be extracted from the $B \to J/\Psi\ K^0_s$ mode, this analysis will suffice. The analysis sequence outlined in the paragraphs above is summarized in Table III.

VI. Conclusions

The SFT offers an opportunity to study B decays at the SSC at a level of statistics more than sufficient to make precision measurements of even relatively small CP violation effects. Furthermore, it has unique capabilities for directly observing the B particles themselves. The relative simplicity of the fixed target experimental configuration makes it possible to take advantage of these opportunities relatively inexpensively.

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