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FIXED TARGET PHYSICS AT THE SSC

F. Grancagnolo

INFN - Sezione di Lecce - Italia

ABSTRACT

This is an extract from the Expression of interest EOI14 for a Super Fixed Target Beauty Facility (SFT) at the Superconducting Super Collider to be built in Texas, USA. It has been presented at the "Workshop on Physics and Instrumentation" held in Aachen, Germany on 4-9 Oct. 1990.

1. INTRODUCTION

The 20 TeV Super Fixed Target B Physics Facility (SFT) contains two major components, the crystal channeling extraction/proton beam transport system and the fixed target beauty spectrometer.

We have considered two general approaches for the SFT spectrometer: open geometry and restrictive geometry. Open geometry gives large acceptance for a wide variety of decay modes and gives the opportunity of tagging, by observation of the second B decay in the event. However, the detector must deal with the full interaction rate. Restrictive geometry spectrometers emphasize rare low multiplicity decays and minimize rates in the detectors per interaction. This type of spectrometer offers simplicity of triggering and cleanliness of event reconstruction. Both approaches seem promising for a 20 TeV fixed target facility. In the sections that follow, we limit ourselves to the open geometry spectrometer which is the more general approach.

Among the topics that can be addressed with the large B statistics obtainable in the SFT are:

1. the measurement of the production of the heavy b quark and the attendant fragmentation and hadronization into the various B hadron species B_u, B_d and B_s;
2. the measurement of the lifetimes of the various species;
3. the determination of the branching ratios for various decay modes;
4. the determination of the mixing of particle and antiparticle;
5. the observation of rare decay modes;
6. the detection and a precise measurement of CP violation effects.

2. FIXED TARGET VS COLLIDER EXPERIMENTS

2.1. Production Rates.

To obtain an estimate of the $pN \rightarrow BB$ production cross at $\sqrt{s}=193$ GeV we have used the third order (in α_s) calculations of K. Ellis et al. which predicts 2.5 to 10 μb total beauty cross section.

Assuming the heavy flavor production increases with atomic number of the target like A^1, the beauty production cross section will be, for pSi, betwen 70 and 280 μb. Taking the total inelastic pN cross section at $\sqrt{s}=193$ GeV to be 38 mb and assuming an A dependence of $A^{0.72}$, we obtain a pSi total cross section of approssimately 420 mb. Therefore, taking into account the thickness of the target (0.075 λ) one gets a production rate of $(1.3 \div 5.2) \times 10^{-4} B\bar{B}$/interaction. Therefore, at an interaction rate of 10^7 interactions/sec (this is essentially limited by the multiple interaction per bucket and by radiation damage), and for a running period of 10^7 sec (one year) one gets: $(1 \div 5) \times 10^{10} B\bar{B}$/year.

While this rate for $\sqrt{s}=193$ GeV pSi interactions is not as great as that expected in the hadron collider configuration $(2 \div 5) \times 10^{11}$ $B\bar{B}$/year), there are aspects of the fixed target configuration which can lead to a greater fraction of the produced B's actually written to tape and eventually reconstructed. In addition, the fixed target configuration offers the unique opportunity of directly observing and measuring some significant fraction of the B's, an option that is available in no other experimental configuration. Thus, the factor of 10 in the yield per interaction between the SSC collider and the SSC fixed target mode becomes much less significant when the unique features, relative simplicity and relative economy of the fixed target experiment, are compared to the formidable challenges and expense of attempting a comparable B collider experiment.

2.2. B Momenta

One of the main points in favor of a fixed target configuration is the much higher momenta of the B's produced in the SSC fixed target interactions compared to those produced in the SSC collider configuration. There are several technical advantages which arise from this high momentum. The high momentum produces very long average decay lengths resulting in the unique situation (among all the options for doing B physics) where B's can pass through many microvertex planes before decaying. In SSC fixed target interactions, an average B will travel 9.5 cm before decaying and pass through approximately 30 silicon planes in the SFT microvertex detector. This allows the possibility of directly observing the B in these spectacular events, and determining whether it is neutral or charged (B_u or $B_{d,s}$). Furthermore, if a magnetic field is imposed on the silicon microvertex detector (an option under discussion), the sign of the charge of the B_u can be determined for a significant fraction of the B_u's. Particle/antiparticle tagging is critical to CP violation measurements but is difficult in other experimental configurations because of the difficulty in determining the charge of the B's from reconstruction of all their secondary decay products. Observation of the charge of the parent B will replace the muon charge as the tag in the case of the $B_u \to \mu$ decays.

Another advantage of the higher momenta of the fixed target configuration is the better track resolution due to the smaller multiple scattering of B decay secondaries.

While it is true that the Lorentz expansion of the decay length is compensated for by the decrease in the average angle of secondaries from B decay such that the impact parameters of these secondaries remain of the same order of magnitude independent of the total center of mass energy, the multiple scattering of the B decay products becomes almost completely negligible in 20 TeV interactions. Thus, the ability to resolve secondary vertices improves. In addition, the negligible multiple scattering in Lorentz boosted 20 TeV events allows the use of more measurement planes leading to the opportunity mentioned above of directly observing the B's.

Higher momentum of the B's also makes possible tractable trigger strategies (in particular trigger strategies based on leptons). For example, muon triggers which depend on the separation of muons from hadrons become difficult if the muon momentum is too low (a muon shield cannot be made thick enough to range out hadrons effectively). The muon momentum is, in fact, low for producing a single muon trigger capable of collecting a large fraction of the B muonic decays in SSC collider events. No such problem exists in the SSC fixed target configuration where the mean and median lepton momenta are 280 GeV/c and 120 GeV/c respectively. The large lepton momentum also helps if an electron trigger is contemplated since distinguishing an electron from a hadron becomes progressively easier for both TRD's and calorimetry as the energy of the electron increases. These more powerful triggers have the advantage of minimizing the required data acquisition systems or on-line microprocessor farms, and the sometimes ignored advantage of reducing enormously the off-line computing load.

2.3. Multiplicity

Another aspect of fixed target events which makes detection and reconstruction of B's easier is the relatively low multiplicity of the events. At $\sqrt{s}=193$ GeV the average event is expected to contain approximately 23 charged tracks and 10 π^0s. This is to be compared with an anticipated multiplicity of over a hundred in a $\sqrt{s}=40$ TeV pp collision. In addition, the B events themselves, at $\sqrt{s}=193$ GeV, have approximately the same low multiplicity (an average of 24 charged tracks). This low multiplicity greatly simplifies beauty triggers based on the hadronic characteristics of B events, as well as off-line reconstruction of B events.

2.4. Overall simplicity and today available technology

The detector components of the SFT themselves can be arranged in a simpler and more economical and effective way than the collider counterparts, even using today's technologies. In particular, the silicon microvertex detector can be a simple, planar arrangement leading to economies of effort and money in construction. The detector can be arranged so that the B decays occur inside itself at most 6 mm before a measurement plane, leading to excellent vertex resolution.

Finally, there is the obvious advantage that the size of a fixed target beauty experiment is very modest because of the small solid angle that must be covered to capture the B decay products. The SFT spectrometer is designed to cover the 3÷75 mrad forward cone. With this coverage, approximately 70% of all B's will have their decay products within the geometric acceptance of the spectrometer at $\sqrt{s}=193$ GeV. If we require that both B's in a given event have all decay products in the acceptance of the spectrometer, a geometric acceptance of 45% is obtained.

In Table I we summarize and compare the important global aspects of the various beauty hadroproduction options.

Table I

Important Parameters of Beauty Production
in Various Hadronic Experimental Configurations

	TeV Fixed Tgt	TeV I Collider	SSC Collider	SSC FixedTgt
Int Rate	10^7-10^8/sec	10^5/sec*	10^7/sec**	10^7/sec
$\sigma(pN \to B\bar{B})$	10nb	20 μb	200-500 μb	2.5 -10 μb
$B\bar{B}/10^7$ sec	10^7-10^8	4×10^8	2×10^{11}-5×10^{11}	1×10^{10}-5×10^{10}
$\sigma_T/\sigma(B\bar{B})$ ***	1.25×10^6	2.5×10^3	$2\div5\div10^2$	$7\div9\times10^2$
Multiplicity	≈15	≈45	~hundred	≈20
$<p_b>$	143 Gev/c	38 GeV/c	51 GeV/c	635 GeV/c
$<p_B>$	118 GeV/c	22 GeV/c	43 GeV/c	445 GeV/c
$<p_\mu>$	32 GeV/c	13 GeV/c	36 GeV/c	280 GeV/c
Median B Decay Length	8mm	1.5mm	3mm	42 mm
Mean B Decay Length	16mm	4.7mm	13mm	95mm

* Present luminosity $\approx 10^{30}$cm^{2}s^{-1} for the Fermilab Collider. Presuming the injector upgrades and corresponding detector upgrades to take advantage of the higher luminosity, this may be increased to 5×10^{31}cm^{2}s^{-1}.

* * 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 heavytargets relative to the total cross section.

3. THE SPECTROMETER

The very important experimental advantages that an SSC fixed target configuration offers must be capitalized on by the design of the SFT spectrometer. The SFT spectrometer (Fig.1) is aimed at taking advantage of the following:

1. long B decay lengths to make direct observations of the B's and to facilitate better tagging;
2. high momentum of the B's and their decay products in the design of the silicon microvertex detector to make higher resolution measurements of the secondary vertices;
3. high momentum of the B's to design efficient, relatively simple triggers which can collect data samples rich in B events;
4. limited solid angle coverage required to capture all B decay products from both B's in a significant fraction of the events.

The SFT spectrometer is 70 meters long and 10 meters wide at its downstream end. The various components of the SFT include two large analysis magnets, a silicon microvertex detector, several stations of PWC wire and pad chambers, a RICH detector, an electromagnetic detector and a muon detector. Optional items under discussion are a 60 kG microvertex detector magnet which is under study for B_u tagging, and the use of silicon planes distributed along the beam to help extend the coverage to smaller angles.

The present design of the SFT calls for the two large aperture analysis magnets to be run with equal and opposite polarities to preserve initial angles in both bend and non-bend planes, simplifying trigger strategies and with the intent of minimizing the spectrometer transverse size.

The configuration of the SFT microvertex detector is similar to the planar silicon microvertex detectors in operation in several Fermilab fixed target experiments. The SFT microvertex detector will be operated as a live target, with the silicon planes providing the target material for the 20 TeV proton beam. The initial "target section" of the SFT microvertex detector consists of 90 planes of 5cm×5cm, 200 micron double sided silicon detectors, spaced 6 mm apart for a total thickness of 4% of a nuclear interaction length and 19% of a radiation length. The silicon measurement planes in the target section will have strip widths of 25 microns. The target region silicon planes will be distributed over a length of 54 cm (one measurement plane approximately every 6 mm).

The "tracking section" downstream of the target region of the microvertex detector will contain 30 additional 200 micron double sided measurement planes distributed over 1.2 meters (one every 4 cm). The second group of silicon detectors is positioned in this extended configuration to provide more lever arm for the measurement of secondaries. The downstream tracking section is 1.3% of an interaction length and 25% of a radiation length. The double sided planes will be 10cm×10cm and have 50 micron pitch.

The remaining components of the spectrometer are mostly standard as far as concepts and designs are concerned.

4. THE TRIGGER

The more prominent features of the B events that can be exploited for trigger purposes are:

1. the presence of a high p_t lepton (from the semileptonic B decays);
2. the presence of a high mass lepton pair (from the $B \to J/\Psi$ decays or the double semileptonic decays of the B and the B);
3. the large total transverse energy and individual track transverse p_t;
4. the presence of secondary vertices.

The $B \to J/\Psi \to \mu\mu$ events are one of the most striking manifestations of beauty production in hadronic interactions and serve as the most powerful method to separate beauty events from the rest of the total cross section. The trigger strategy proposed here takes advantage of the special attributes of $B \to J/\Psi \to \mu\mu$ decays to produce a trigger with a large rejection of brackgrounds, yielding an extremely favorable ratio of trigger to interactions.

In addition, the dimuons act as a starting point for the offline analysis, reducing the amount of reconstruction that must be performed on each recorded event and enabling excellent offline rejection of backgrounds since the observation of a J/Ψ from a secondary vertex unambiguously insures that an event contains a BB pair. We also emphasize here that $B \to J/\Psi$ decays are among the most interesting from the standpoint of searching for CP violation in B decay. There are several decay modes ($B \to J/\Psi + K^o_S$, $B \to J/\Psi \pi^+ \pi^-$, $B \to J/\Psi \phi$ for example) for which the final state is CP conjugate, making them the most promising avenue to measuring CP violation.

The $B \rightarrow \mu + x$ semimuonic decays offer different challenges and opportunities. Two features of the $B \rightarrow \mu + x$ semileptonic decays are very different from the $B \rightarrow J/\Psi$ modes and are very important. First, as pointed out above, the charge of the muon "tags" the decaying B so that some knowledge is gained about its particle or antiparticle nature. This is important for both mixing and CP studies. In addition and most importantly, the $B \rightarrow \mu + x$ decays are far more copious than the $B \rightarrow J/\Psi \rightarrow \mu\mu$ decays. In events containing a BB pair, semimuonic decay will produce a muon approximately 23% of the time and approximately 42% of these muons will have a $p_t > 1.5$ GeV/c. Muons with a p_t this large are quite unusual; semileptonic decays of pions, kaons and charm produced in 20 TeV/c interaction contain muons with this magnitude of p_t in less than 1 interaction in 10^4. Therefore, high p_t muons provide a distinctive signal on which to trigger.

Level I will require detection of one or more muons, as defined by the triple coincidence of an aligned set of pads in the projective pad geometry of three or more layers of Resistive Pad Chambers (RPC), embedded in the steel of the SFT muon detector. The minimum energy required for a muon to penetrate the SFT muon detector steel and produce a signal in the RPC's is 19 GeV in the central part of the acceptance and 15 GeV at wider angles. Studies of simulated $\sqrt{s}=193$ GeV events show that the probability for a minimum bias event containing a muon with more than 20 GeV from π or K decays in flight is of order 1→2%. A further reduction of the Level I trigger rate can be achieved by imposing a very rough minimum p_t requirement on the muons detected by the RPC's. In a scheme in which the accepted muon coincidences are defined by means of Programmable Logic Gate Arrays (PAL's), it is trivial to include only three-plane patterns consistent with a given p_t threshold. Although the p_t resolution achievable at this level is limited, it is adequate to provide the additional factor (two or three) required to fit the trigger rate confortably within the Level II bandwidth. Alternatively, one can achieve the same goal by imposing a threshold on the total transverse electromagnetic energy of the event as determined by the SFT EM detector. Level I would be pipelined and would take less than a couple of hundred nanoseconds.

We plan to develop a Level II trigger for the SFT which would perform complete online tracking in a couple of microseconds. As presently planned, this trigger level will increase the rejection of the total cross section by:

1. imposing the requirement that the muon have 1.0 to 1.5 GeV of transverse momentum and that several tracks with intermediate p_t be present in the event, thereby increasing the probability that the selected events contain high mass B hadrons;

2. examining the silicon microvertex detector for the presence of secondary vertices.

Given that the above two conditions can be applied independently of each other, it will be possible to optimize the signal to background ratio of the accepted events by tuning the parameters of the two requirements.

The overall rejection to be provided by the Level II trigger is about a factor of 50, an extremely modest requirement in view of the many different event features on which the trigger can operate. Given an expected input rate of the order of 5×10^4 events/s into Level II, one should think in terms of a processing time of about 2 microseconds, which would limit the dead-time to 10% even without the added complication of a pipelined system. We envisage reaching such a time performance while accomplishing a full track recognition by making use of associative memory pattern recognition.

In Table II below, the cumulative effect of all the acceptances, efficiences and cuts on the muons from $B\to J/\Psi\to\mu\mu$ and $B\to\mu+x$ decays have been estimated using Monte Carlo estimates of the efficiences of various detectors. The geometric acceptances in Table II have been calculated using PYTHIA for $B\to J/\Psi\to\mu\mu$ modes and semileptonic $B\to\mu+x$ modes.

Table II
$B\to J/\Psi\to\mu\mu$ and $B\to\mu+x$
Muon Acceptances and Efficiencies

	$B\to J/\Psi\to\mu\mu$	$B\to\mu+x$
Level I		
Geometric Acceptance for muon tracks (including steel attenuation)	0.85	0.87
Level I detector efficiences	0.74	0.86
Level II		
Level II detector efficiences	0.80	0.80
Multihadron and Secondary Vertex Requirements	0.70	0.70
Level II p_t cut efficiency for muons	0.95	0.42
Composite Acceptance/Eff. for single or dimuons triggers	0.33	0.18

The trigger rate reduction factors per interaction are shown in Table III below:

Table III

Expected Trigger Suppression Factors per interaction

Trigger Level	DiMuon Trigger	Single Muon Trigger
I	$O(10^{-4})$	5×10^{-3}
II	10^{-1}	2×10^{-2}
I × II	$O(10^{-5})$	$O(10^{-4})$

5. PROTON EXTRACTION BY BENT CRYSTAL CHANNELING

The extraction is initiaded in the East Utility straight section of the SSC, just south of the East Campus.

The counterclockwise circulating proton beam is bent by 0.7 mrad with the first of a dogleg set of dipoles placed at the beginning of the straight section. After about 50 m, a 3 mm × 3 mm transverse size and 3cm long silicon channeling crystal is positioned. The crystal is bent so as to supply an effective 100 μrad deflection to the portion of the beam which intercepts it and is channeled.

Approximately 200 m downstream of the crystal, where the channeled beam has been deflected by 20 mm, there is a set of 16 Lambertson magnets which leave the channeled beam undisturbed and bend back the unchanneled portion of the beam by 1.4 mrad into the last dipole of the dogleg set.

The beam transport which follows is the least innovative feature of the SFT and serves the only purpose of directing the beam to the spectrometer trying to avoid the muon vectors from the dumped beams.

As far as the process of crystal channeling is concerned, there are two main questions to be analyzed: one is the channeling efficiency and the other relates the difficulty of bringing the protons, in the desired quantity, onto the crystal.

Minor questions address: the difficulty of bending the crystal by only 100 μrad (i.e. 3 μm for a 3 cm crystal); the reproducibility of the crystal alignment; the flatness of the surface of the crystal (septum thickness);

the purity of the crystal and, possibly, the heating effects on the crystal.

Four are the main contributions to the dechanneling efficiency of a crystal. The first contribution is due to the multiple scattering of the beam off the electrons in the crystal. This is limited to about 4% given the high momentum of the beam and the short length of the crystal. The second contribution is due to the angular acceptance of the crystal. Also here the contribution is limited to about 4-5% given the critical angle of 1 μrad and the angular spread of the beam (.4 μrad). The bending dechanneling, which is the third contribution, is less than about 20% because of the very small bending angle, 100 μrad, and therefore the very favourable ratio p/R=0.67 GeV/c/cm. The last contribution is due to the surface acceptance of the crystal. By taking into account the Thomas-Fermi radius for Si, one gets a cross sectional area of the crystal not available for channeling of about 16%.

The overall efficiency of channeling, therefore, is of the order of 65% after a single pass through the crystal. One can reasonably assume that, after many turns, a global efficiency of about 85% is reached.

More serious is the problem of the illumination of the crystal by the proton beam. Many strategies have been studied so far, starting from the obvious one of placing the crystal in the periphery of the beam halo and scraping off the desired amount of protons.

The current strategy relies on a two step procedure: first, create a high dispersion point, where the crystal is going to be placed, by changing the optics of the accelerator lattice next to the straight section and, secondly, create a halo in the beam by increasing the momentum of the off-momentum protons with a filtered rf noise, analogously to what has already been done at LEAR.

The combined effect should ensure the desired result.