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Lattice/Beam Dynamics Working Group
Summary Report*

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Introduction

The Lattice/Beam Dynamics Working Group was charged with reviewing and identifying technical issues and their potential solutions for (a) a 2x2 TeV high luminosity p-pbar collider, and (b) a 30x30 TeV high luminosity pp collider. Rather than attempting to solve very specific problems for these devices in the relatively short time scale of a workshop, the group attempted to look at more general questions to try to indicate in which directions future work in these areas should procede. The emphasis of the group tended toward lattice issues and general accelerator design issues for the above two cases, with more specific questions being addressed as directed by the needs seen by the Workshop Synthesizers.

Since this was a Workshop, formal presentations were kept to a minimum. A few, slightly more "formal" Working Group presentations were made during the workshop on topics such as a "Mobius Accelerator" (R. Talman), "Robinson Wigglers" (S. Y. Lee), "Phase Trombones" (A. Garren) and the "CERN LHC Combined Function Lattice" (R. Talman). Most of these were results of discussions which occured during the course of the workshop.

2 TeV x 2 TeV

Lattices

For the 2 TeV pbar-p collider, the lattice discussion consisted of a review of work performed at Fermilab in 1988-89 on Tevatron upgrade lattices.[1] In this work, several alternatives were investigated, including:

a) lengthening of the long straight sections in the Tevatron from 53 m to 73 m. This option required two different dipole magnets, with fields of 8 T and 9 T (for 1.8 TeV beams). The strong dipoles were used in the vicinity of the straight sections.

b) lowering the ring dispersion function by using new quadrupole magnets/trims near the straight sections to match the dispersion to the standard cells of the arcs. The dispersion peaks were reduced from 6 m to under 4 m.

c) increasing the cell length in the arcs from 30 m to 40 m. The existing Tevatron arcs contain "missing dipole magnets" at the "17" and "48" locations; this new design has the same amount of free space, but with the missing magnets arranged to better control the dispersion mismatch. Dispersion suppressors are used at the ends of the arcs to make zero dispersion straight sections. While the geometry of this accelerator is slightly different than that of the existing Tevatron, the radial excursions within the tunnel were estimated to be typically 6-9 in., with a maximum of 13 in.

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Table 1 shows general parameters of the above three cases. The general conclusion was that while a new Fermilab accelerator would be constrained by the Tevatron tunnel, it is possible to make improvements to the lattice design to provide longer straight sections, better matched lattice functions, and perhaps both. With the introduction of 90^0 cells, the dispersion function is lowered substantially, and this phase advance along with the smaller beam size for coalesced bunches may improve the performance of the separated beams accelerator.

Table 1

	TEV	OPT1	OPT2	OPT3	
Energy	1.0	1.8	1.8	1.8	TeV
Radius	1000	1000	1000	1000	m
Str. Sect. Length	53	73	53	53	m
Cell phase adv.	68	74	90	90	deg
Cell β_{max}	98	98	99	135	m
Global β_{max}	110	110	180	144	m
Cell D_{max}	4.0	3.5	2.6	4.7	m
Global D_{max}	5.9	5	3.6	5.6	m
D in str. sec.	2.5	3.2	2.4	0.0	m
Magnet field	4.4	8,9	8.0	7.8	T
Cell Quad Strength	0.038	0.041	0.050	0.036	1/m
Cell Half-length	29.7	29.7	29.7	39.7	m

Beam Intensity Issues

Two beam intensity issues of the 2 TeV pbar-p collider were discussed. The first involved the impedance thresholds for the parameter sets provided by the Workshop Synthesizers. The longitudinal impedance threshold for the microwave instability was computed to be on the order of $Z_{||}/n = 2$ Ohms, and was not believed to pose any new technical challenges. The transverse impedance of the accelerator needs to be less than about $Z_{\perp}/n = 800$ kOhms/m, which also is not pushing any presently obtainable limits.

The second intensity issue looked at for the pbar-p collider was the long-range beam-beam interaction. This collider will have 1-2 orders of magnitude more long-range interactions than the present Tevatron collider. As an estimate of the magnitude of the effects, consider a head-on beam-beam tune shift of $\Delta\nu_{HO}$ for each of two interaction points. Around the accelerator, there will be $2*n_B$ long-range interactions, where n_B is the number of bunches in each beam. Assuming the two beams are separated by several beam sigmas (4-5, say) by the helical orbit separators, then a proton bunch will produce a long-range force on the antiproton bunch which is decreasing roughly as $1/r = 1/(d \pm x)$. (Here, d is the separation between the centers of the two bunches, and x is the displacement of an antiproton from the center of it's bunch.) The expansion of $1/(1 \pm x/d)$ generates all

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multipoles, giving rise to steering errors, tune shift errors, chromaticity, and tune spread. For simplicity, if we assume a simple 1-D model, then these errors can be written in terms of $\Delta\nu_{HO}$ as:

a) $(\Delta x_{co}/\sigma)_{max} \approx 4\pi\, \Delta\nu_{HO} / (d/\sigma) = 0.025$

b) $\Delta\nu = 2\, \Delta\nu_{HO} / (d/\sigma)^2 = 0.0008$

c) $\Delta\xi = 4\, \Delta\nu_{HO}\, (D/\sigma) / (d/\sigma)^3 = 3.2$

(D is the dispersion function = 4 m, say, and take $\sigma = 0.4$ mm at $\beta = 100$ m)

d) $\Delta\nu_{max} \approx 9\, \Delta\nu_{HO} / (d/\sigma)^4 = 0.00014$
(for particles at $a = 2.4\,\sigma$)

where these expressions are for a single long-range encounter. The numerical results are for $\Delta\nu_{HO} = 0.01$, and $d/\sigma = 5$. One can see that the effects of hundreds of such encounters (1500, for one parameters list considered) will give rise to substantial operational problems for this accelerator. The most recent parameters list for the 2 TeV accelerator reduces the number of long-range interactions to 216, which makes some of the numbers more tolerable, though the issues remain, especially for chromaticity compensation. The analysis should be carried through further, looking at the details of the 2-D long-range interactions along the helical orbit. In addition, the effects of uneven bunch spacing (which is surely to be the case for scenarios with several hundred bunches) need to be investigated -- in particular, the Pacman effect due to average corrections of the long-range beam-beam interactions.

30 TeV x 30 TeV

For the 30 TeV x 30 TeV Collider, most of the discussion was centered around optimization of the lattice. Drawing upon the lessons from the SSC, the group felt that simplification of the lattice -- from a hardware standpoint -- was absolutely necessary. This entailed developing a workable lattice in which the number of different types of components are minimized, long cable runs for correctors are avoided and the number of power leads are minimized. This philosophy led to a design with "sparse/lumped" correctors, and assumptions about having power and vacuum hardware physically attached to the same cryostat containing the main quadrupole magnets, thus avoiding the need for separate "spool pieces" in every half-cell.

The group also held discussions on magnet aperture and field quality, and instabilities thresholds. Impedance issues were not seen to be an immediate issue which could be addressed by this group in this workshop. The prominent impedance issue will be the beam tube liner, and so will depend very strongly on the magnet and cryogenic/vacuum design.

One of the more exciting aspects of the new accelerator was the possibility of reducing the transverse emittance damping time due to synchrotron radiation by a factor of 2 or 3. The Working Group also spent time on the design of a standard cell to perform this function.

Lattice Issues

It was realized by the Working Group that the lattice of a new, large, high energy collider could be simplified in such a way that may have a significant impact on the cost of the accelerator. The emphasis on much of the discussion was how to avoid the need for "spool pieces," which are devices used in present superconducting accelerators to interface the accelerator to power and vacuum systems, beam instrumentation systems, and which typically contain accelerator correction magnets. In the SSC, each 90 m half cell of the Collider ring contained a 5 m spool piece, at least half of which was used for correction magnets -- dipoles, quadrupoles, and sextupoles in particular, with occasional other correctors such as skew quadrupoles. There were a variety of spool pieces, some of which contained recooling apparatus, some having power and vacuum interfaces, different ones with different corrector packages, etc.

The Working Group envisioned a scenario as follows. The "arcs" of the accelerator are made up of 90^{0} FODO cells. Each FODO cell is composed of a quadrupole and 5 dipole magnets. As a working example, the Working Group compared these concepts to the general lay-out of the SSC arcs. In the SSC, roughly every 24 cells there was an interface point to the power and cryogenics systems. In the new scheme, the lattice would contain a section of 4 cells which would have free space generated by leaving out a sequence of dipole magnets (10, in our example) as a "dispersion-matched insertion." These "free spaces" would contain "empty cryostats," which could then be converted to function as spool pieces as required. That is, there would be devices which are of the same length and outer diameter as standard dipole cryostats, but which may contain correctors, power feeds, cryo feeds, etc. as needed. An example of such an insertion is shown in Fig. 1.

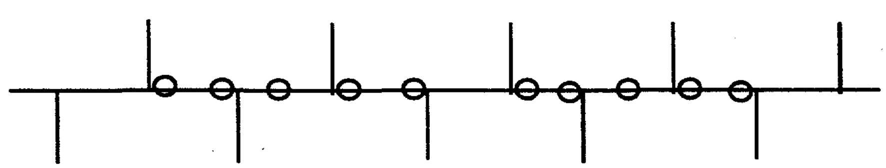

Fig. 1

To avoid having spool pieces in each half cell, standard systems hardware, which occurs every cell, would be designed into the quadrupole assembly resulting in a single piece of hardware. It was assumed that the quadrupole stands would be remotely moveable with stepping motors to perform orbit adjustments throughout each arc. In regions such as the IRs and utility straight sections (not discussed by this Working Group), steering correction magnets could be implemented (as well as in the free-space insertions discussed above, as necessary) to perform injection bumps, etc.. However, in the arcs, where such distortions generally are not necessary, the quadrupole alignment could be set and left alone. To make a 5 mm orbit bump in the ring, one would need only about ± 1 mm movement of a standard quadrupole. Such remotely controllable magnet stands could also allow one to relax the alignment requirements of the accelerator upon installation. It was pointed out, however, that if this accelerator incorporates a 2-in-1 magnet design, simultaneous alignment of both beams using moveable magnets may be more difficult operationally.

The adjustment of the global tunes of the accelerator will be performed by Phase Trombones -- one at each end of each arc. These consist of 5 "standard" cells with 5 independently controlled quadrupole circuits, allowing one to tune the phase advance across the Trombone in each plane, while keeping the section matched to the rest of the ring. If it is found that such sections cannot meet the required tuning range (roughly 1-2 units), then other measures would need to be considered, the most straightforward being the placement of trim quadrupoles in the "free-space" insertions.

Chromaticity adjustments will be made using sextupoles in the free-space insertions. In our example, each insertion contains four straight sections by F quads, four next to D quads, each the length of a standard dipole. It was felt that this would be plenty of space to encorporate the sextupoles necessary for chromaticity correction. Naturally, the effects on dynamic aperture of such a lumped scheme will have to be studied carefully.

In addition, the free-space insertions contain "missing magnets" in the middle of half cells, which can contain skew quadrupoles to perform decoupling.

A schematic layout of one arc of the accelerator is shown in Fig. 2

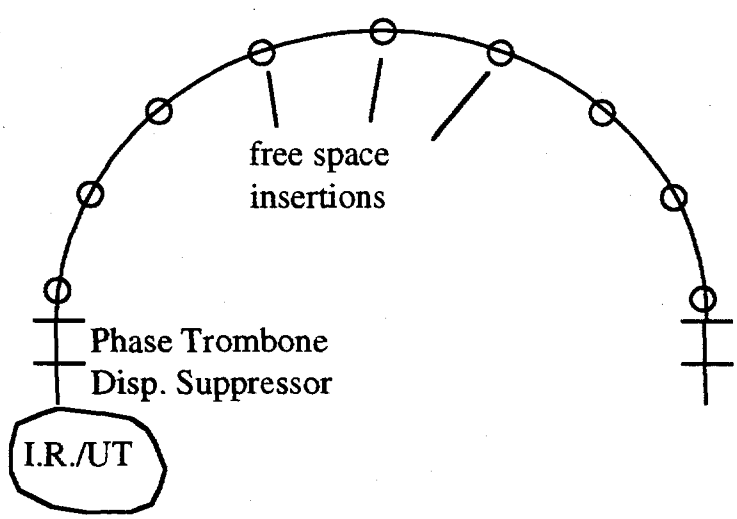

Fig. 2

Damping Time Enhancement

The damping rates, or damping partition numbers, of the collider are constrained to add up according to Robinson's Theorem[2]:

$$J_x + J_y + J_s = 4,$$

where $J_x = 1-\mathcal{D}$, $J_y = 1$, and $J_s = 2+\mathcal{D}$. Here, $\mathcal{D}$ is given by

$$\mathcal{D} = < (D/\rho^2)(1/\rho + (2B'/B)> / <1/\rho^2>$$

where the averages are taken over the entire ring. For a pure FODO lattice, where B'=0 when B is not zero, and vice versa, then $J_x = J_y = 1$, and $J_s = 2$. To take advantage of the synchrotron radiation damping inherent in a 30 TeV proton collider, schemes were investigated to enhance the damping rate. A design of a combined function lattice for the LHC[3] was reviewed by the group, and a combined function lattice was briefly discussed for the 30 TeV ring. This was initially discussed in the spirit of simplifying the componets of the standard cell. But, it was quickly realized that the pure combined function lattice would lead to anti-damping in the horizontal plane. Next, two lattices consisting of defocusing bending magnets were envisioned. The first lattice used cells containing a single focusing quadrupole and defocusing bending magnets elsewhere. Analytical expressions for this simple system were developed. Though the hardware layout is simple (one quadrupole type, and one bending magnet type), to obtain increased damping one needs a gradient of about 3 T/m in a 10 T magnet. ($\mathcal{D} \approx 2<DB'/B> = -1$, which for B=10T, and <D> = 1.5 m leads to B'=-3 T/m.) This leads to rather long cells (if we demand 90^0 phase advance in both planes) and unacceptable amplitude functions. The second lattice used defocusing bending magnets, but retained both F and D quadrupoles in the standard FODO-type structure. In this case, the two quadrupoles are of different strengths (lengths), and so one gives up the simplicity one was after.

Another, simpler scheme involves misaligning the quadrupoles by roughly 5 mm. If the otherwise standard quadrupole magnets are all moved radially outward by this amount, then the quadrupoles will steer the beam and hence generate radiation. For this case,

$$\begin{aligned} \mathcal{D} &= -(8\,\delta / (L\,\theta_b))\,(L_b/L_q) \\ &= -(8\,\delta / ((90\text{ m})(7.5\text{ mrad})))\,(80\text{ m})/(5\text{ m}) \\ &= -1 \\ \longrightarrow \delta &= 5.5\text{ mm},\ \text{for SSC-type cell parameters.} \end{aligned}$$

The 5.5 mm shift would thus double the transverse damping rate. On the other hand, it may be more economical or simpler to design a quadrupole magnet with a small central bend field of order 1.2 T to perform the same task. And, if the quadrupole positions are remotely tunable, as we have previously assumed, then one could contemplate "tuning" the damping rate.

Magnet Apertures

One afternoon's discussion focused on magnet aperture issues. It was the concensus of the Working Group that a 50 mm magnet design was acceptable for a 2 TeV x 2 TeV pbar-p collider. For the 30 TeV x 30 TeV collider, the group held the assumptions that this accelerator would use a 2 TeV injector, and would have a fill time of under 30 minutes. For this case it was felt, primarily from SSC experience, that ±5 mm were required for a "good field region," and ±10 mm of physical aperture was required to perform injection and beam abort procedures. It was felt that the field quality generated by present 50 mm magnets was satisfactory. Because the nonlinear field quality suffers in a minor way by going through the magnet off-axis, one could consider having the 20 mm beam pipe off-center through the (presumed) 50 mm magnet bore, if this simplified any engineering efforts of the vacuum/liner designs. It was later noted that if full advantage of synchrotron radiation damping enhancements can be realized in this collider -- by appropriate choice of lattice, or quadrupole offsets, for example -- then the field quality at injection could perhaps be relaxed. In this scenario, a smaller magnet bore, or lower injection field might be tolerable.

Bibliography

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[3] F. Meot and T. Tortschanoff, "Combined Function Focusing, Combined Function Superconducting Dipole for the LHC," CERN **SL/94-20(AP)**, CERN, 1994.