FERMILAB SITE-FILLERS AS CAMEL* PROTOTYPES

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Summary

At Snowmass, beam energies greater than about 10 TeV dominated the intellectual efforts related to hadron-hadron colliders. The anticipated cost and scope of these machines spurred the search for cost-cutting innovations and for a suitable site, perhaps in the southwestern desert. (Given its probable location and method of design, CAMEL* seems an appropriate acronym for such a facility.) A prototype of more modest time-scale, cost, and energy is needed to bridge the physics gap until completion of CAMEL and to establish the feasibility of various proposed technologies. Building a prototype at Fermilab would reduce its cost, speed its completion, and improve its performance by taking advantage of existing real estate and expertise and by exploiting fully the potential capabilities of existing facilities (injectors, antiproton accumulator, etc.). The design and expected performance of various Fermilab site-filling (R = 2.4 km) antiproton-proton colliders are discussed here. Other options are also described. A separate paper by Mantsch[1] in these proceedings presents some cost estimates.

Antiproton-proton Colliders

A single-ring antiproton-proton site-filling (R=2.4 km) collider is proposed as the first step in the elaboration of existing Fermilab facilities. So-called "superferric" magnets[2], which are powered by superconducting coils but in which the field strength and uniformity are primarily determined by the properties of the iron, may be the best choice for the first ring. They will easily reach 2 Tesla and show promise for early development as a simple, economical, reliable CAMEL dipole. However, if equally promising higher-field magnet designs are developed, they should obviously be used to increase the energy and luminosity of the site-limited prototype. A low filling factor (bending radius/average radius) of 0.7 is chosen partially for numerical convenience (2 Tesla dipoles give 1 TeV beam energy) but primarily to allow considerable room for straight sections and quadrupoles. (A high tune will be shown to be desirable.)

Compared to the Tevatron I project[3] at Fermilab, a site-filler would give full-time dedicated operation at higher luminosity for several detectors without interference to/from the fixed-target program. The center-of-mass energy in TeV would be numerically equal to the magnetic field strength in Tesla. The expected performance of Fermilab site-filling antiproton-proton colliders can be found by scaling from the design performance of the Tevatron I project. (In particular, the antiprotons would come from the same accumulator.) Tevatron I aims for a luminosity of at least 10^{30} cm^{-2}sec^{-1} for beam energies of 1 TeV, in a ring with 1 km radius and 4.4 Tesla dipole magnets. The antiproton collection rate is $3\cdot10^{7}$ per second or about 10^{11} per hour, the luminosity lifetime is greater than a day, the invariant emittance is $24\pi\times10^{-6}$m, and the β function is 1 m at the crossing point. For simplicity, the Tevatron I values of invariant emittance and β function will be used throughout this paper; the reader can easily scale to other values.

For head-on collisions of two round($\varepsilon_x=\varepsilon_y=\varepsilon=6\pi\sigma^2/\beta$, $\beta^*_x=\beta^*_y=\beta^*$) Gaussian beams consisting of M bunches each, the luminosity L is given by

$$L=\frac{3f_{rev}Mn_{\bar p}n_p}{(\varepsilon_p+\varepsilon_{\bar p})\beta^*}$$

where f_{rev} is the revolution frequency, n_p ($n_{\bar p}$) is the number of protons (antiprotons) per bunch, and ε_p ($\varepsilon_{\bar p}$) is the transverse emittance of the proton (antiproton) beam.

The tune shift Δν suffered by the antiproton beam per encounter with a proton bunch can be written

$$\Delta\nu=\frac{3r_o n_p}{2\gamma\varepsilon_p}$$

where r_o is the classical radius of the proton and gamma is the usual relativistic energy to mass ratio. Note that the bunch-bunch tune shift depends only on the ratio of the number of particles per bunch to the invariant emittance. The average number n_i of interactions per bunch-bunch encounter is related to the total cross section σ_{tot} by

$$n_i=\frac{L\sigma_{tot}}{Mf_{rev}}$$

It is instructive to rewrite the luminosity in a form which directly displays its dependence on the factors which limit it. Using the following relations,

$$\varepsilon_p=\varepsilon_{\bar p}$$

$$n_{\bar p}=N_{\bar p}/M$$

$$n_p=2\gamma\varepsilon_p\Delta\nu/3r_o$$

$$f_{rev}=\frac{\beta c}{2\pi R}=\frac{ec\,B_{av}}{2\pi m_p\gamma}$$

the luminosity can be rewritten:

$$L=\left[\frac{ec}{2\pi m_p r_c}\right]\left[\frac{N_{\bar p}B_{av}\Delta\nu}{\beta^*}\right]$$

The luminosity can be increased (with some difficulty) by varying the factors in the second bracket; varying the factors in the first bracket is beyond the scope of this paper. For an invariant emittance of 24 $\pi\times10^{-6}$m, a useful expression for numerical calculation is

$$L=1.01\times10^{30}\,\mathrm{cm^{-2}sec^{-1}}\,\frac{n_{\bar p}(10^{11})\,n_p(10^{11})\,M\,E_b(\mathrm{TeV})}{R(\mathrm{km})\,\beta^*(\mathrm{m})}$$

Consider beams containing 10^{11} particles per bunch. The formation and stability of such bunches are discussed in the Tevatron I Design Report. At the design collection rate of 10^{11} antiprotons per hour, it takes M hours to collect M bunches and the total beam intensity $N_{\bar p}$ is M×10^{11}. For the invariant emittance of $24\pi\times10^{-6}$m, the tune shift per bunch-bunch encounter is 0.003, a safe value.

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*Collider-Accelerator of Maximal Energy and Luminosity

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Suppose first that there are three bunches in a 1 TeV, 2 Tesla ring. The luminosity is then 1.25×10^{30} $cm^{-2}sec^{-1}$, a cross section of 60 mb gives 1.27 interactions per bunch-bunch encounter, and the total tune shift around the ring resulting from six head-on bunch-bunch encounters is a tolerable 0.018.

To raise the luminosity further without raising the tune shift or the number of interactions per bunch-bunch encounter, it is necessary to use more bunches. Then the beams must be separated except at the detectors in order to keep the total tune shift around the ring tolerable. For bunched beams, electrostatic fields offer a feasible method of beam separation. Not only must the beam separation be zero at the detectors, but the crossing angle must also be kept small. This suggests an arrangement with electrostatic plates on both sides of each detector to set up an undulating closed orbit with an integral number of oscillations between detectors. To avoid excessive electric field strength requirements, the separators should be located at the high-β locations occuring as a byproduct of the low-β insertions. The resulting constraints on tunes, phase advances, available free space and so forth can probably be incorporated in a new lattice designed for colliding beams (but are not easy to satisfy when adapting existing rings to collider use). One bunch per betatron wavelength can be separated in this way, so the total number of bunches is limited by the machine tune. That is one reason for choosing a high tune, say 50.

In a day, 24 bunches of antiprotons can be accumulated and, with separators, accommodated in the collider. The luminosity is then 10^{31} $cm^{-2}sec^{-1}$ with the same 1.27 interactions per bunch-bunch encounter at 1 TeV.

The luminosity can be increased further by raising the number of bunches and/or the energy. With 50 bunches in a 5 TeV ring, a very respectable luminosity of 10^{32} $cm^{-2}sec^{-1}$ is attained. There is one bunch-bunch encounter per microsecond, a very convenient rate for the experimenter. The tune shift has stayed the same but there are now 6.4 interactions per encounter, or even more if the cross section rises with energy. Some experiments with good shielding and/or limited acceptance may tolerate this rate, but if a lower rate is required the luminosity must be reduced. Excessive antiproton collection times might be avoided either by future improvements in the collection rate or by reducing the emittance and the number of particles per bunch.

Other Options

It seems likely that a single ring of appropriate design could be used not only as an antiproton-proton collider but also as an electron-positron facility. The low magnetic fields required could be produced by allowing the magnets to warm up and running current through the normal conductor included in the superconducting cable. Adapting the proposed ring to electron beam is facilitated by its high tune and by the large amounts of free space available for installation of RF. Methods must be incorporated to cope with the large amounts of synchrotron radiation.

Scaling quadratically from the PEP energy of 18 GeV for a radius of 350 m implies a beam energy of 47 GeV for 2.4 km. The center-of-mass energy of 94 GeV is fortuitously close to the expected mass of the neutral intermediate boson, making the facility a potential Z^0 factory.

The electrons and positrons could be produced by targeting protons, then accumulated in a damping ring[4] and accelerated as high as 30 GeV in the Main Ring before injection into the site-filling ring. The magnetic field in the site-filler would then range from 600 to 900 gauss.

Adding a second ring in the same enclosure is an attractive future possibility. It is reasonable to hope that by that time an economical and reliable superconducting dipole of very high field (say 10 Tesla) will have been developed. Such a ring opens the prospects of antiproton-proton collisions at 5 TeVx5 TeV with moderate luminosity, of 5 TeVx1 TeV proton-proton collisions with very high luminosity, and of 47 GeVx5 TeV ep collisions. A direct comparison of the physics output of these options and of the cost and performance of low and high field superconducting magnets would provide invaluable guidance for the design of the ultimate desert machine.

References

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3. Design Report, Tevatron 1 Project, Fermilab, October 1982.

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