"CONVENTIONAL" 20-TEV, 10-TESLA, $p^{\pm}p$ COLLIDERS

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Summary

The performance of various 20-TeV colliders is discussed assuming 10-Tesla bending magnets. For bunched beams, the luminosity for $\bar{p}p$ collisions will be approximately $\langle n \rangle \times 10^{31}$ cm^{-2} sec^{-1} where $\langle n \rangle$ is the average number of interactions per bunch collision desired by the experimenters; for pp collisions this becomes $\langle n \rangle \times 10^{32}$ cm^{-2} sec^{-1}. Values of $\langle n \rangle$ up to 25 can be accommodated in a straightforward manner. Continuous beam pp collisions may yield a luminosity of 10^{33} to 10^{34} cm^{-2} sec^{-1} if the large amount of energy in the intense beams can be handled. Assuming that adequate and reliable 10-Tesla magnets can be built without unforeseen difficulties, the construction cost of such a collider, together with its new laboratory in the desert, would cost 2 to 3 billion dollars (FY-82 dollars) using present-day, "conventional" techniques. Although such a machine appears straightforward to build, considerable R&D will be required in order to optimize the design and bring down costs.

General Features

Site

At 10-Tesla, 42 kilometers of dipole magnets are required to bend a 20-TeV beam through 2π radians. For the purpose of discussion here we have assumed a machine circumference of 60 kilometers; this includes some contingency for correction elements, long straight sections, and the possibility that in a radiation environment "10-Tesla" magnets may in fact only operate reliably at a somewhat lower field.

The circumference is roughly ten times that of the present Fermilab Main Ring and will require a flat, uninhabited site of diameter ~ 15 miles. This will presumably involve the establishment of a new laboratory in the western desert; depending on the exact location, it might also imply the construction of an associated "science city" for the staff and their families. The site selection is further complicated by the requirements of access, water, and ~ 100 MW of power.

Injector System

Several options were briefly considered; while a detailed design (and some R&D) will be required to choose the optimum injector/booster system, there does not appear to be any fundamental problem. The costs of the injector system, although substantial, are not dominant. To provide a definite framework for discussion, we took the following set of accelerators:

	E_{min} TeV	E_{max} TeV	B Tesla	C kilometers	
Linac	0	~ 0.01			
First Booster	~ 0.01	0.2	1.4	4	common
Second Booster	0.2	1.4	10	4	tunnel
Main Ring	1.4	20	10	60	

As discussed below, the specifications on both the beam emittance and $\bar{p}$ collection scheme impact the injector design.

An important parameter which needs better understanding is the allowable dynamic range of superconducting accelerators; persistent currents at low field distort the field uniformity. The Energy Saver/Doubler (ESD) at Fermilab is designed to operate over a range of only 1000/150 ≈ 7; ISABELLE is designed to operate over a range 400/30 ≈ 13. If this ratio can be pushed further with an economical magnet, it would help to reduce the cost of the injector system.

The injector system is roughly the size of the present Fermilab accelerator system. In his talk at Snowmass, the Fermilab Director suggested that a cost-saving alternative might be to move the existing accelerator system to the new desert site. This could be especially attractive in the case of the new ESD ring; the lower energy boosters are less expensive and may well need to be different from those presently in use at Fermilab if the emittance and $\bar{p}$ source requirements for the 20-TeV collider are to be met.

$\bar{p}$ Source

With the above injector system, Leemann and Lambertson[1] have designed a $\bar{p}$ collection and cooling system expected to produce 10^{12} cooled $\bar{p}$'s per hour. This design is based on the recent Fermilab TeV I design[2], but achieves an order of magnitude faster collection rate by having a debuncher ring with twice the transverse emittance acceptance in both dimensions and by taking 6×10^{12} protons on target every 2 seconds. This latter number is twice the TeV I design and may require target sweeping. The increased cooling rate would be made possible by a stochastic cooling system with a frequency bandwidth of 4 GHz (4 to 8 GHz); this is somewhat higher in frequency than is presently being developed for TeV I (2-4 GHz) and will require R&D.

To produce the $\bar{p}$'s, 6×10^{12} protons would be accelerated to 120 GeV in the First Booster and compressed into a series of short bunches. This would produce 6×10^{8} $\bar{p}$'s at 10 GeV into an acceptance of $\varepsilon_x = \varepsilon_z = 40\pi \times 10^{-6}$ m (not normalized) and $\Delta p/p = 4\%$. The momentum spread would be reduced in the debuncher ring (circumference ≈ 0.7 km) to

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0.25%; rapid transverse precooling would also take place in the debuncher (a factor 10 in emittance). The $\bar{p}$'s would then be transferred to an accumulator ring (same circumference as the debuncher) where the longitudinal density would be increased by a factor of 130.

Every 200 seconds 6×10^{10} $\bar{p}$'s are rf unstacked from the core in the accumulator ring, accelerated to 200 GeV, and transferred to the Second Booster. After five such transfers are made, filling the booster circumference, these $\bar{p}$'s would be rf stacked and adiabatically debunched (ISR mode of stacking). After 12 hours, for example, one would have accumulated 1.2×10^{13} $\bar{p}$'s with $\Delta p/p \sim 5 \times 10^{-3}$ at 200 GeV. These would be appropriately transferred to the Main Ring and, together with protons circulating in the opposite direction, accelerated to 20-TeV.

Emittance

Low transverse emittance of the beams is important if good luminosity is to be achieved with a relatively small number of particles. This is obviously desirable in order to reduce $\bar{p}$ collection time, and makes easier the extraction septa and beam dumps; it also reduces the radiation heating of the superconducting coils by beam losses and lessens the refrigeration load due to synchrotron radiation.

For the study here we assumed a normalized emittance of

$$\varepsilon_n = 10\pi \times 10^{-6} \text{ meters;}$$

this can be compared to the (20-30) $\pi \times 10^{-6}$ m presently obtained at the Fermilab main ring and CERN SPS. At 20-TeV, we would then have

$$\varepsilon = \varepsilon_n/\gamma = 0.47\pi \times 10^{-9} \text{ meters,}$$

where ε is the emittance containing 95% of the beam. For Gaussian beam shapes the rms width of the beam in each transverse dimension is

$$\sigma_x = \sqrt{\varepsilon\beta/6\pi}$$

where β is the usual betatron amplitude parameter. For $\beta^* = 2$m at the interaction region, at 20-TeV

$$\sigma_x^* = \pm 13 \text{ μm}.$$

At $\beta_{max} = 400$ m in the lattice, the beam size is

$$\sigma_x = \pm\ 0.18 \text{ mm}.$$

Several schemes were considered at the Summer Study to reduce the emittance even further, say to $\pi \times 10^{-6}$ m. E. Knapp described a linac based on the PIGMI[3] technology to accelerate protons up to a few GeV at the cost of ~ \$10M/GeV for the machine itself (i.e., excluding buildings, etc.). This would allow injection into the First Booster at sufficient energy to overcome space-charge dilution.

C. Ankenbrandt[4] suggested another scheme in which a booster ring of radius ~ 75 m is used to accelerate H^- ions to about 5 GeV. These ions would be extracted and then charge-exchange injected into the next ring; this arrangement would allow the flexibility to stack in whichever dimension was least critical for the job at hand, maintaining a small longitudinal emittance when accelerating protons to produce $\bar{p}$'s or a small transverse emittance for colliding beams.

A third method, put forward by Leemann and Lambertson[1], involves stochastic cooling of the beams at 200 GeV in the Second Booster. With an 8-16 GHz system, they estimate that a beam with normalized emittance of $10\pi \times 10^{-6}$ meters could be cooled to $\pi \times 10^{-6}$ meters in about one hour; such a large bandwidth pass system clearly needs R&D.

A major uncertainty lies in whether the beams can be maintained at a small emittance over several days; various instabilities, including the effects of beam-beam interactions, will tend to enlarge the beams. As discussed below, synchrotron radiation damping has the potential to reduce the emittance by a large factor.

It would be extremely useful to investigate experimentally the limits on emittance using existing machines; this is particularly crucial if lower-field machines are to be considered seriously, since the number of particles required to fill the larger circumference of such machines would be excessive if the emittance cannot be maintained at a small value.

Aperture

The cost of the machine will depend strongly on the required magnet aperture. As noted above, the beam itself will be quite small. However, allowance must be made for orbit excursions, both unintended distortions and those for injection, extraction, and (in the case of $\bar{p}p$) separation of the beams so that they collide only where desired. For a machine tune of $\nu = 60$, it was calculated at the Les Diablerets study[5] that an rms scatter of ±0.25 mm in quadrupole positions would result in an orbit distortion of 12 mm, while a random error of $\pm 10^{-3}$ in the dipole field would result in a distortion of ~ 13 mm. Higher tunes would magnify the first effect, while reducing the second effect.

In the case of high field superconducting magnets, the conductor placement errors may put a limit on the winding diameter if the magnetic field uniformity in the region of the beam is to be within tolerance.

As discussed below, for a given tune the transverse resistive wall instability is proportional to $(R/r)^2$ where R is the radius of the machine, and r is the radius of the vacuum chamber; control of this instability at high frequencies during injection may set a lower limit on the vacuum pipe diameter, particularly for lower field machines with large R.

For this study we assumed that a 5 cm inner diameter beam pipe was tolerable. R&D on the many aspects controlling this diameter must be undertaken if an optimized machine, both economical and reliable, is to be built.

Tune

For purposes of discussion we assumed a tune of $\nu \approx 60$. This is considered to be a "relatively weak" tune, and there was considerable discussion of the pros and cons of a stronger tune. As discussed below, the longitudinal instability is easier to handle in a machine with a low tune, while the opposite is true for the transverse resistive wall instability. Similarly, as discussed above, low tunes reduce the orbit distortion due to quadrupole misalignment, while the opposite is true for that due to dipole field errors. Because of the smaller transverse beam size at a higher tune, the excitation of higher order instabilities is also smaller. On the other hand, the higher tune requires more and longer quadrupoles, and this costs money, both to buy the quadrupoles and to build a longer tunnel to house them. This cost might be offset, however, if it allowed the use of a smaller bore.

As an example of the lattice, we quote the "weak" focusing case of the Les Diablerets ICFA study.[5] With $\nu = 60$ and a phase advance of 90^{o} per cell, a curved half-cell would have 100 m of 10-Tesla dipoles and a 3.2 m long 250-Tesla/m quadrupole. The beta function would vary from 70 to 400 m in the lattice and the dispersion function from 2.3 to 4.8 m. Doubling the tune would result in twice as many quadrupoles, each nearly twice as long (5.9 m).

Synchrotron Radiation

At the high energies and fields considered here, synchrotron radiation will play an important role; it is both a curse and a blessing. The energy loss of 190 keV/turn at 20-TeV and 10-Tesla must be made up with a low level rf, even for the "continuous beams" case (by using a very high-frequency system, the rf structure would not be seen by the detectors and the duty cycle would effectively still be 100%). The corresponding power lost from the beam will be 1.5 kW/10^{13} protons. This is not troublesome for those scenarios with 10^{13} circulating particles, but care would be required at 10^{15} particles to avoid collecting a substantial fraction of the 150 kW of power at 4^{o}K. The synchrotron radiation will strike the beam pipe at a small angle, and hence can be largely reflected, and "rattle" down the pipe to special catchers at a higher temperature.[6]

The damping time of the emittance in each transverse plane is given by the time in which the particle would radiate away its energy, $\tau = E/(dE/dt)$. For 10-Tesla magnets at 20-TeV, $\tau \sim 6$ hours; ignoring other factors, this would imply an improvement in luminosity by a factor of e every six hours. Assuming beam lifetimes of at least a few hours, this damping could prove to be quite useful. The radiation is soft ($E_c \approx 400$ eV) compared to electron machines and the equilibrium emittance given by quantum fluctuations quite small. The final equilibrium size will be a balance between the damping and various instabilities and noise (including beam-beam interactions).

The damping time scales with energy and magnetic field as

$$\tau \propto 1/EB^2.$$

For a fixed magnetic field, $\tau \propto 1/E$; once a machine is built with a fixed radius, $\tau \propto 1/E^3$. A 20-TeV machine built with 2.5 Tesla magnets would have $\tau = 4$ days at the top energy.

Bunched $\bar{p}p$ Machine

Luminosity

The luminosity of bunched beam machines will be set by the desired average number of interactions per bunch collision, $\langle n \rangle$, and the distance required between bunches, d. The optimal value for $\langle n \rangle$ is determined by the physics being studied, by the detector resolution and overlap times, and, in some cases, by the amount of computer time available to unscramble the interactions.

For rare events with a robust signature, such as high-mass $\mu^+\mu^-$, tens of interactions per bunch collision may be desirable. Interactions leading to jets of very high $p_\perp$ may also be best studied at high rates. For example, Gordon et al.[7] examined the case in which $\langle n \rangle = 10$ using Monte Carlo methods. They assumed a 40 × 40 array of calorimeter towers covering a pseudorapidity of ±2 units and full 2π in azimuth. For each bunch collision, they found the interval of $\Delta y = 1$ and $\Delta\phi = \pi/2$ (roughly the size of a "jet") showing the largest $p_\perp$ (taking only those towers with $p_\perp > 1$ GeV). They found that $\langle$ largest $p_\perp \rangle \sim 4.5$ GeV with an rms of ±2.6 GeV; this latter number is considerably less than the calorimeter measurement error for a 100 GeV jet, $\sigma_E \approx \pm 50\%/\sqrt{E} = \pm 5$ GeV.

Other types of physics may require a single, clean interaction per bunch crossing. The maximum number of beam collisions with n = 1 is obtained for $\langle n \rangle = 1$, in which case $1/e = 37\%$ of the beam collisions have n = 1; in most cases, beam collisions with n > 1 can be easily rejected by observing multiple vertices along the interaction region.

The minimum distance between bunches is determined by the requirement that the beam orbits be separated before the beam bunches can collide at their next meeting point. For the $\bar{p}p$ case, this separation must be accomplished using electrostatic separators on each side of each interaction region, as shown schematically in Fig. 1. The proton and antiproton orbits then execute betatron oscillations abut one another until they reach the next separator at the next interaction region.

This scheme imposes severe constraints on the lattice design. Not only must the separators be located with phase advance from one to the next to give an integer (or half integer) number of oscillations, but the correction system is more complicated. For example, the sextupoles used for chromaticity control will also have an effective quadrupole field at the separated beams.

For maximum effect, the separator must be placed where the beam trajectories are relatively parallel (large β). In the example shown, a 700-cm long separator with 65 kV/cm gives a kick of

$$\theta = \mathcal{E}\ell/E = 65 \text{ kV/cm} \times 700 \text{ cm}/20 \text{ TeV} = 2.3\ \mu\text{rad},$$

compared with the beam spread of $\sigma = \pm 0.17$ μrad (β = 2700 m). After the kick, the separation of the two beams at location z is given by

$$s(z) = \pm\left[\beta(z)\left(\beta\theta^2\right)_{kick} \sin\left(\phi(z) - \phi(z_{kick})\right)\right]^{1/2}$$

where $\phi(z)$ is the betatron phase at z. For the simple insertion shown this results in a separation of $\pm 5\sigma$ at

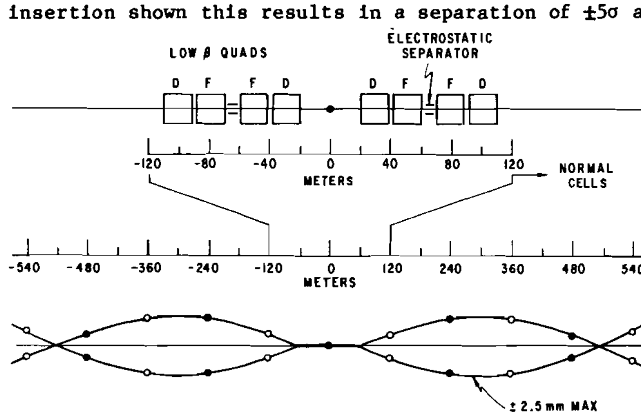


Fig. 1. Sketch of the $\bar{p}p$ separation method. The solid circles indicate the position of the bunches at the time of collision; in order for the bunches to be well separated at the next meeting (open circles), they must be separated by $\gtrsim$ 240 m.

120 meters from the interaction region. This is considered to be a "safe" separation, so that two bunches can pass one another at this point without undue influence. Taking into account the relative motion of the beams, bunch meeting regions 120 m apart implies a distance between bunches of ~ 240 m = 800 nsec.

For a total cross section of 100 mb, the luminosity integrated over a bunch collision is

$$L = 10^{25} \langle n \rangle \text{ cm}^{-2}.$$

For a bunch separation of d = 240 m, this leads to a luminosity

$$\mathscr{L} = Lc/d = 1.25 \times 10^{31} \langle n \rangle \text{ cm}^{-2} \text{ sec}^{-1}.$$

Since the value for d is pretty much fixed by the separator strength available and the geometry, the luminosity is mainly determined by the familiar conflict between rate and cleanliness.

$\langle n \rangle = 1$ Case

The number of particles per bunch, N, required to achieve $\langle n \rangle = 1$ is given by

$$L = \frac{N^2}{4\pi\sigma^2} = \frac{3}{2}\frac{\gamma N^2}{\varepsilon_n \beta^*} = 10^{25} \text{ cm}^{-2}.$$

For γ = 20 TeV/$M_p c^2$ = 2.13×10^4, $\varepsilon_n = 10\pi \times 10^{-6}$, β^* = 2m (betatron amplitude function at crossing point),

$$N = 1.4 \times 10^{10} \text{ per bunch.}$$

Since we have 60 km/240 m = 250 bunches per beam, we need a total of

$$N_{\bar{p}} = 3.5 \times 10^{12}.$$

This would require 3.5 hours of collection time at our assumed rate of 10^{12} $\bar{p}$'s/hour. For a lower-field ring, the same luminosity would require a collection time proportional to the circumference, or $\tau_{col} \approx 35$ hours/B(Tesla).

The beam-beam tune shift per beam collision point can be expressed as

$$\Delta\nu = \frac{3}{2}\frac{r_p N}{\varepsilon_n} = \frac{r_p \beta^*}{\gamma N} L,$$

where $r_p = e^2/M_p c^2 = 1.53 \times 10^{-18}$ m, the classical proton radius. For the $\langle n \rangle = 1$ case considered here

$$\Delta\nu = 1.0 \times 10^{-3},$$

well under the value of 5×10^{-3} canonically taken as the limit for long term beam stability.

This low tune shift may allow a doubling of the number of bunches, thereby making the distance between bunches 120 m. At the two bunch crossings 60 m on either side of the interaction point, the bunches would not yet be inside the separators and would hence still collide head-on. The total tune shift (spread) per revolution would then be $3 \times 6 \times 10^{-3} = 0.018$, still acceptable, and the luminosity would double to $\mathscr{L} = 2.5 \times 10^{31}$ cm^{-1} sec^{-1} for $\langle n \rangle = 1$.

Scaling with $\langle n \rangle$ and ε_n

As can be seen by inspection of the formulae above, the scaling with $\langle n \rangle$ goes as

$$N \propto \Delta\nu \propto \sqrt{L} \propto \sqrt{\langle n \rangle}.$$

For $\langle n \rangle = 25$, we obtain

$N = 7 \times 10^{10}$/bunch,

$N_{\bar{p}} = 1.8 \times 10^{13}$ total (18 hours collection)

$\Delta\nu = 0.005$

$\mathscr{L} = 3 \times 10^{32}$ cm^{-2} sec^{-1}.

Higher values of $\langle n \rangle$ could be achieved without violating the $\Delta\nu$ limit if both ε_n and N were increased linearly with $\langle n \rangle$.

If experiments in the various interaction regions were to desire different $\langle n \rangle$, one would load up the machine to satisfy the highest $\langle n \rangle$, and then adjust the β^*'s to give the desired $\langle n \rangle$ values. This will require flexible, well-matched insertions.

As mentioned previously, a smaller emittance would reduce the number of particles required. For a given luminosity,

$$N \propto \sqrt{\varepsilon_n},$$

$$\Delta\nu \propto 1/\sqrt{\varepsilon_n}.$$

For example, taking $\varepsilon_n = \pi \times 10^{-6}$ meter ($\times$ 1/10 in both transverse dimensions compared to our standard case), for $\langle n \rangle = 1$

$N = 0.44 \times 10^{10}$/bunch (1.3 hour collection time),

$\Delta\nu = 3.2 \times 10^{-3}$.

Instabilities

Here we consider the effects of both the longitudinal and the tranverse coherent instabilities.[8,9] Although feedback dampers can be used at low frequencies, at high frequencies one must rely on the beam to heal itself through Landau damping.

The longitudinal (microwave) instability requires a minimum full width at half maximum momentum spread in the beam if the beam is not to blow up,

$$\left(\frac{\Delta p}{p}\right)^2 \gtrsim \frac{I_{max}}{E/e}\,\nu^2 \left|\frac{Z_{||}}{n}\right|,$$

where I_{max} = 0.7 amp for an effective bunch length of 1 meter and 1.4×10^{10}/bunch ($\langle n \rangle = 1$). We assume that by paying careful attention to maintaining a "smooth" vacuum chamber, the effective longitudinal impedance for the nth mode, $|Z_{||}/n|$, , can be held to < 5Ω. Although this is lower than measured values for SPEAR and ISR, estimates as low as 1Ω have been made for more modern storage rings.[10] At 20-TeV, we need $\Delta p/p \gtrsim 0.25 \times 10^{-4}$; even going to 7×10^{10}/bunch ($\langle n \rangle = 25$), the limit $\Delta p/p \gtrsim 0.55 \times 10^{-4}$ is not troublesome. This limit is eased at lower energy for a given longitudinal emittance, so there is no additional consideration necessary at injection.

The transverse wall instability requires a (half) tune spread of

$$\Delta\nu \gtrsim \frac{I_{max}}{E/e}\frac{R}{2\pi\nu}\,|Z_\perp|$$

in order to damp the high frequencies where feedback cannot help. The effective transverse impedance, $Z_\perp$ is related to the longitudinal impedance, $Z_{||}$, as

$$|Z_\perp| \approx \frac{2R}{r^2}\frac{|Z_{||}|}{n} \quad .$$

For machine and vacuum chamber radii of R = 10 km and r = 2 cm,

$$Z_\perp \approx 2.5 \times 10^8 \ \Omega/\mathrm{m} \quad .$$

Even for the $\langle n \rangle = 25$ case, the requirement $\Delta\nu \gtrsim 1.2 \times 10^{-3}$ is still quite manageable at 20-TeV.

At an injection energy of 1-TeV, one would have to increase the tune spread to 0.023 or reduce I_{max} by lengthening the bunch. This could become a problem at injection if the R/r^2 factor is increased substantially by the use of lower field and/or smaller aperture magnets.[8] A more careful examination, both theoretical and experimental, of this point must be made if we are to seriously consider such options.

Bunched pp Machine

The big disadvantage to pp colliders is the need for a second ring of magnets (or in a recent Brookhaven scheme, two-apertures threaded through a common iron core). The major advantage to pp is the possibility of increased luminosity. A secondary advantage is not having to build and operate a $\bar{p}$ source, and the related ease of rapidly filling the machine.

Since the beam orbits are easily separated by a magnetic field before and after the interaction region, the bunches can be more closely spaced than was the case for $\bar{p}p$. An example is given in Fig. 2 in which the bunches can pass one another safely at 15 m, i.e., distance between bunches d = 30 m = 100 nsec. This gives

$$\mathscr{L} = 10^{32} \langle n \rangle \ \mathrm{cm}^{-2} \ \mathrm{sec}^{-1} .$$

If the detector can take the same $\langle n \rangle$ every 100 nsec as it could every 800 nsec for $\bar{p}p$, then a factor of 8 in event rate has been gained. In practice, this gain over the $\bar{p}p$ case may well only be a factor of 2 to 5 for many detectors; the gain may also be reduced by a factor of 2 if indeed the $\bar{p}p$ bunches can be allowed to collide three times per interaction region.

The total number of protons is more than in the $\bar{p}p$ case, and this will require care in beam handling and some attention to the effects of synchrotron radiation on refrigeration. For $\mathscr{L} = 10^{33}$ cm^{-2} sec^{-1} ($\langle n \rangle = 10$ every 100 nsec), a total of 1.8×10^{14} protons would be required for the two beams.

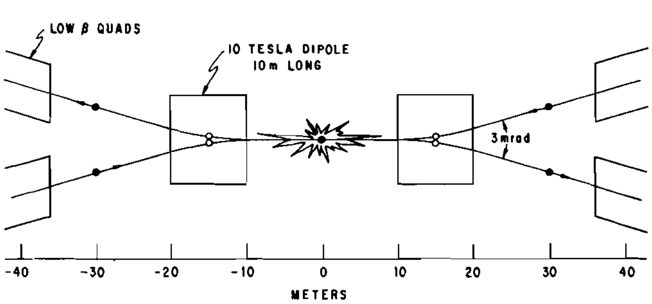


Fig. 2. Sketch of the pp separation scheme. Here the bunches (solid circles) can be spaced by ~ 30 m and still be well separated when they next pass one another (indicated by open circles).

A possible problem with pp colliding beams is ensuring that the beams properly collide head on. This may be important since the beam-beam interaction appears to be more virulent when the beams are offset from each other by a distance comparable to the rms width of the beams. Experience with this effect in electron rings varies, and needs to be studied under more carefully controlled conditions at low energies (weak damping). If this effect is important, it would mean that the two rings will have to be carefully aligned with relatively weak beams, and then reloaded with the desired intense beams which could be quickly and accurately kicked into head-on collisions. This may be difficult to achieve with the precision required.

Continuous Beam pp Machine

Depending on the detector and the physics being investigated, a higher luminosity may be useful with the better duty cycle which can be obtained from continuous beams colliding at an angle. This is the mode that has been used successfully at the ISR for many years. Our present case is somewhat different, however, in that we must make up the synchrotron radiation losses. By using a high frequency rf accelerating system, say $\gtrsim$ 1 GHz, the duty cycle will still be effectively 100%. This does mean, however, that we will have bunched beams crossing at an angle and grazing one another. The stability of such a regime needs to be better understood and may require even higher frequencies if the bunches are to experience symmetric forces from the other beam in the crossing region. An alternative would be to run with truly continuous beams, following their energy loss with a gradual decrease in the magnetic field; periodically one would take the beams out of collision, carefully rebunch them, accelerate back up to 20-TeV, and then debunch. We ignore such complications here and simply treat the beams as continuous.

At a distance L much larger than β^*, the rms width of the beam is approximately

$$\sigma = \sigma^* L/\beta^*$$

where σ^* is the rms width at the crossing point. For a crossing angle α, the beam separation at L is

$$s = L\alpha = (\beta^*\alpha/\sigma^*)\sigma = \eta\sigma \quad .$$

We would like well-separated beams away from the interaction region and take $\eta = 10$ as a minimum separation. For the same parameters as used in the bunched case ($\epsilon_n = 10\pi \times 10^{-6}$m; $\beta^* = 2$m in each dimension), at 20-TeV this gives a crossing angle of 62 μrad. The rms length of the luminous region is given by

$$\sigma_\ell = \sqrt{2}\,\sigma^*/\alpha = \pm 0.28 \ \mathrm{m} \quad .$$

The luminosity is approximated by

$$\mathscr{L} = \frac{c\lambda^2}{\sqrt{\pi}\ \sigma^*\alpha} \quad ,$$

where c is the velocity of light and λ is the line number density of protons in each beam. To achieve a luminosity of 10^{33} cm^{-2} sec^{-1}, $\lambda = 0.68 \times 10^{10}$/meter, and for a 60 km circumference, the two beams would comprise a total of 8×10^{14} protons with an energy of 2500 MJ and would emit 120 kW of synchrotron radiation. This line density is comparable to that in the Fermilab main ring:

$$\lambda_{MR} \approx 3 \times 10^{13}/6 \ \mathrm{km} = 0.5 \times 10^{10}/\mathrm{meter} \quad .$$

The beam-beam tune shift coming from the crossing region is then

$$\Delta\nu = \sqrt{2/\pi}\ \frac{r_p \beta^* \lambda}{\gamma \sigma^* \alpha} = 1.0 \times 10^{-3} \quad ,$$

well under the canonical 5×10^{-3}. There is an additional long-range tune shift, calculated to be[11]

$$\Delta\nu_{\ell r} = 0.56\ \frac{\ell_s \sigma_\ell'}{(\beta^*)^2}\ \Delta\nu \quad ,$$

where ℓ_s is the distance from the crossing point to the nearest point where the beams can be shielded or bent away from one another. For $\ell_s = 10$ m,

$$\Delta\nu_{\ell r} = 0.4 \times 10^{-3}.$$

Going to $\mathscr{L} = 10^{34}$ might even be possible with our standard emittance if means can be devised to handle the 2.6×10^{15} protons (8000 MJ, 380 kW synchrotron radiation); $\Delta\nu = 3 \times 10^{-3}$ in this case.

As with the bunched pp mode, it may be difficult to hold the beams steady to the precision needed to ensure proper collision.

Trade-Offs Between High and Low Magnetic Fields

High-field magnets at 10 Tesla clearly need considerably more superconductor and stronger clamping structure than low-field magnets at ~ 2.5 Tesla. The conductor placement is also somewhat more critical in the high field magnets, and, depending on the superconducting material, they may well have to operate at a lower temperature, say 1.9°K. There are, however, several advantages to the four times smaller circumference of a 10-Tesla machine:

1. The high field results in a smaller machine, allowing a wider choice of sites; it may be very difficult to find a flat site forty miles in diameter with adequate water, power, and accessibility.

2. The "linear" construction costs would be reduced by a factor of ~ 4. These costs include not only the tunnel, but also utilities, vacuum systems, roads, etc. The optimum choice of field depends critically on how far these costs can be reduced while still maintaining a reliable, operable system.

3. The operating costs would be reduced with a smaller size machine. One could easily commute the 20 miles each way to an experiment on the far side of the ring, but not 80 miles; the alternative of centrally locating all experimental areas needs further study of costs and adverse effects of one-fold symmetry on the machine.

4. The transverse instability which goes as $R^2/r^2\nu$ would be 16 times worse for a machine radius R increased by a factor of four, unless compensated by large $r^2\nu$.

5. The synchrotron radiation damping time would be 16 times longer in the low field case, 4 days at 20 TeV, instead of 6 hours.

6. The number of particles required for a given luminosity would be a factor of four higher in the low-field case. This means a factor of four longer collection time of antiprotons for a $\bar{p}p$ collider, and a factor of four increase in the number of particles which must be handled by systems such as the rf and abort.

Cost Estimates

At a summer study, cost estimates must be based primarily on scaling from past projects or from proposed projects which have been carefully engineered and estimated. In this spirit, we first examine the original Fermilab construction costs, a total of \$245M, most of it spent in the early 1970's. Preoperation and equipment money are not included, nor are the many improvements added since the initial construction. To reproduce the initial Fermilab complex today would cost a factor of about 2.5 times this amount due to inflation; as an estimate of the costs in today's dollars, we show in parentheses the ~ 1971 costs multiplied by a factor of 2.5 (units are \$M):

Split of 245 total		(612)
General Facilities	50	(125)
Experimental Areas	70	(175)
Accelerators	125	(312)
Split of 125 for accelerators		
Transfer/Controls	20	(50)
Linac	20	(50)
Booster	20	(50)
Main Ring	65	(162)
Split of 65 for Main Ring		
Components (installed)	45	(112)
Services	8	(20)
Tunnels and Buildings	12	(30)

As a naive first estimate of the construction cost of a 20-TeV $\bar{p}p$ collider laboratory in the desert, we assume the following (FY82 \$M):

General Facilities — 125
This buys roughly the equivalent of the initial Fermilab complement; it could be an underestimate since this lab will presumably need more people and facilites, and we may have to build a "science city."

Experimental Areas — 60
Assume six areas like the BO (CDF) area now under construction at Fermilab, each with its own "industrial" buildings.

Accelerators

Injector/Boosters/Transfers/Controls — 312
Same as initial Fermilab complement of accelerators; this may be an underestimate if a linac injector of several GeV is used to maintain a small emittance.

$\bar{p}$ Source — 100
A bit more expensive than the TeV I source (but 10 times faster collection and cooling).

20-TeV Main Ring — 1620
Ten times the Fermilab main ring cost. The Saver magnets (4.2 Tesla) appear to cost about as much as did the original conventional magnets (2 Tesla) after correction for inflation. Here we simply assume that a 10-Tesla system can be done for about the same price per foot.

\$2217M

Table 1

Dipole Magnet Design Parameters

	Saver	5T	10T
Coil I.D., mm	76	50	50
Temp., K	4.5	4.5	2.0
J_c(NbTi), A/m^2	1140	1780[1]	825[1]
Cu/S.C. ratio	1.8	1.8	0.85
Overall, A/mm^2	320	572	400
Coil O.D., mm	110	71	110
Iron I.D., mm	192	100	240
Iron O.D.,(average) mm	350	250	430
Coil Area, mm^2	2850	1270	4760[2]
Iron Area, cm^2	692	420	1840
Conductor Cost \$/lb.[3]	46.9	49.4	61.5

1) $B_{max}/B_o = 1.1$

2) Graded; Area graded/Area non-graded = 0.8

3) W. Hassenzahl, LBL-14918, "Cost of High Field Nb_3Sn and NbTi Accelerator Dipole Magnets," October 1981.

This does not include the detectors, preoperation monies, etc. The corresponding estimate for a 10-TeV $\bar{p}p$ collider plus laboratory would be about \$1400M.

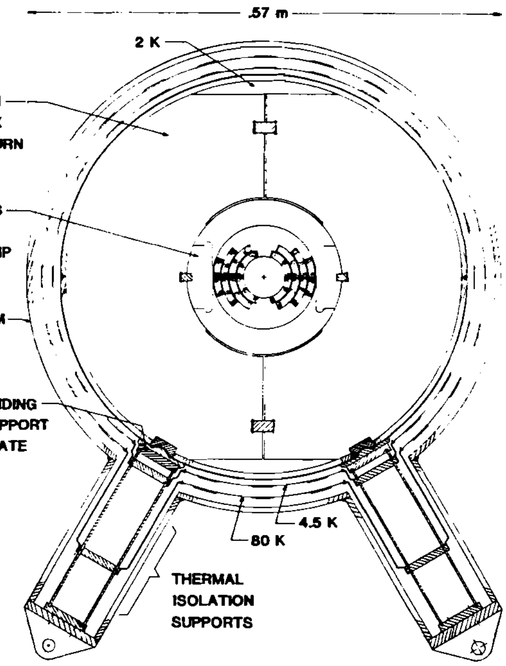
A more careful estimate was made by C. Taylor at this study based on the preliminary design of a 10-Tesla dipole shown in Fig. 3. Parameters of this design (and a 5 T design) are given in Table 1. This magnet would have four layers of NbTi cable wound on a 50-mm bore, and would operate at ~ 1.9^{o}K. It would have cold iron with an outer diameter of ~ 17 inches. The magnet costs (FY-82\$), shown in Table 2, were scaled from the Fermilab Saver magnet costs.

The resulting estimate for a single 20-TeV main ring of 10-Tesla magnets is shown in Table 3 to be approximately \$1.6B, including a 50-km circumference tunnel similar to the Fermilab Main Ring. The estimates scaled from the initial Fermilab construction as discussed previously for general facilities, experimental areas, injector/booster system, and $\bar{p}$ source add \$0.6B for a total of \$2.2B for a 20-TeV $\bar{p}p$ laboratory. The corresponding two-ring pp laboratory would cost approximately \$2.9B.

Table 2

Dipole Magnet Cost Estimate

	FNAL-Saver			
Materials	K\$/Magnet	K\$/m	K\$/m	K\$/m
Conductor	13.0	2.17	1.02	4.8
Coil Parts	4.8	0.80	0.80	0.80
Cryostat	4.0	0.67	0.67	1.0
Iron	3.5	0.58	0.35	1.55
Misc.	2.0	0.33	0.33	0.33
Total K\$	27.3	4.55	3.17	8.48
Labor (Hours)				
Coil Assy.	200	34	22	44
Cryostat Assy.	200	33	22	40
Iron Assy.	80	13	11	13
Final Assy.	120	20	13	20
Total Hours	600	100	68	117
Labor Cost (K\$) (\$20/hr.)	12.0	2.0	1.36	2.3
Total K\$	39.3	6.55	4.53	10.78



10T 50mm BORE DIA DIPOLE MAGNET WITH "COLD" IRON AND LOW HEAT-LEAK SUPPORTS

Fig. 3 Sketch of 10-Tesla NbTi superconducting magnet.

Table 3

20-TeV Facility Cost Estimate (M\$)

	5T		10T	
Main Ring	1 Ring	Δ for 2 Ring	1 Ring	Δ for 2 Ring
Magnets	420	420	500	500
Test Facility	20	10	15	5
Factory (5 yr. prod.)	25	10	20	10
Prototypes	15		20	
R&D	80		160	
Vacuum System	40	40	20	20
RF, Ejection Sys. Contr., Correct P.S. Beam Instr.	120	100	95	70
Refr. System	60	60	75[1]	75[1]
Tunnel and Utilities (8 K\$/M)	800		400	
Total	1580	640	1305	680
EDIA 20%	316	128	261	136
Total-20 TeV Main Ring	1896	768	1566	816
Rest of Laboratory				
General Facilities	125		125	
Experimental Areas	60		60	
Inj/Boosters, etc.	312		312	
$\bar{p}$ Source	100	-100	100	-100
Total, 1 ring $\bar{p}p$	2493		2163	
2 rings pp	3161		2879	

1) 2^{o}K

These estimates for 10-Tesla facilities are \$300 M lower than those for 5-Tesla (although the high-field magnets are technically uncertain at present). This is in contrast to estimates made by Palmer that indicated that the costs for rings with 5-, 7-, and 10-Tesla magnets would be very similar. This discrepancy points out the fact that reliable cost estimates will require the careful prototyping of specific magnet designs, including demonstration of field quality, reliability, and low heat leaks with suitable production techniques. Several different designs will have to be examined in some detail if an optimal choice is to be made.

R&D Needed for $p^{\pm}p$ Colliders

It is clear from the above cost estimates that R&D on several fronts is urgently needed if the U.S. program is to be able to afford a 20-TeV collider. Such R&D could ultimately save an enormous amount of money for a relatively modest investment. Many areas requiring R&D have been identified in the preceding sections and we summarize them here:

1) Theoretical and experimental work to determine the minimum allowable magnet bore:
   - a) magnet field quality required to avoid resonances;
   - b) resistive wall instability control;
   - c) orbit distortion and its correction;
   - d) injection/ejection requirements.

2) Prototype various magnet designs, with engineering to reduce production costs while maintaining field quality, reproducibility, and reliability:
   - a) superferric (2-3 T),
   - b) iron-free (6 T),
   - c) high field (10 T),
   - d) two-in-one magnets.

3) Determine the maximum practical dynamic range of superconducting accelerators: E_{final}/E_{inj}.

4) Reduce costs of conventional construction and installation:
   - a) trenching, pipe laying techniques;
   - b) remote adjustments (robots);
   - c) scenarios for installation and repair work;
   - d) cheap, but adequate buildings and services.

5) Improve beam cooling techniques, both stochastic and electron cooling:
   - a) increase $\bar{p}$ collection rate and reliability;
   - b) reduce beam emittance at ~ 200 GeV;

6) Theoretical and experimental work to find the limitations on emittance and the sources of dilution.

7) Determine crucial factors which depend on tune; design lattice and insertions.

8) Devise abort and beam dump systems for 20-TeV beams of various intensities.

9) Systems studies to determine optimum magnetic field and areas for further cost reduction.

Conclusions

Using "conventional" methods, it would cost two to three billion dollars (FY-82\$) to construct a 20-TeV $p^{\pm}p$ collider at a new laboratory. This estimate already assumes that reliable 10-Tesla magnets of suitable aperture can be built for roughly 1.6 times the cost per meter of length of the present Fermilab 4.2-Tesla, 3-inch bore Saver magnets; demonstration of this will require considerable R&D.

Ingenious ideas are needed to bring down this cost if such a machine is to become reality. The accelerator subgroup of Huson et al. examined some possibilities such as cheap superferric magnets and inexpensive accelerator tunnels; these ideas must also be followed up with R&D. In addition to "adiabatic" improvements, we will eventually need "discontinuous" inventions if we are to continue on the path to ever-higher energy. Almost by definition, it is difficult to predict the form these inventions might take. Much higher field gradients, perhaps using lasers, is one possibility; another would be the development of superconductor capable of operating at much higher temperatures. Such inventions may well be the outgrowth of developments made in fields of science and technology far from those we have traditionally dealt with in the past; nonetheless, we should attempt to identify promising areas and give them whatever encouragement we can.

We conclude that a "conventional" 20-TeV $p^{\pm}p$ collider appears quite feasible, with luminosities in the range 10^{32} to 10^{33} cm^{-2} sec^{-1}. Because of the high cost, however, it will require many (if not all) of the following conditions:

1) a healthy economy;
2) a sympathetic government;
3) substantial R&D progress;
4) international collaboration.

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