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20 TEV UPGRADE FOR THE TEVATRON (March 15, 1994)

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I. Introduction

There is general agreement among scientists and even congressmen that there is important new physics to discover if a 20 on 20 TeV hadron-hadron collider of adequate luminosity could be built. The main mission of the Drell subpanel is "defining a long-term program to pursue the most important high energy physics goals ..." For the last ten years there has been strong unanimity among U.S. high energy physicists to do $\sqrt{s}$ = 40 TeV physics. A major goal is to solve the problem of the electro-weak symmetry breaking which involves "where do the masses come from?" or finding the Higgs particles. Now that LEP has shown that there are 3 and only 3 families of leptons, I, for one, feel not only is the Standard Model still on track but this is a sign that we may be on the final path to the Theory of Everything. It is hard for our country to evaluate the monetary worth of a collider which could achieve this goal. But the U.S. in the last few years has been willing to spend over 1 billion dollars per year on high energy physics. I now will try to outline how this 20 TeV goal can be achieved within a total high energy physics budgetary limit of ~$700 million per year. I also am assuming some of the older programs will be shut down. The trick is to make 20 TeV the next upgrade at Fermilab and use proton-antiproton collisions rather than proton-proton collisions. One of the new developments which makes such a low cost feasible is the existing Main Injector upgrade. The Tevatron as fed by the Main Injector can also serve as the injector for a new 20 TeV ring and provide a luminosity of ~10^{33}.

If there are no delays, the construction and design period might be the usual 10 years. In addition, a new physics program could start within 5 years by fitting the Tevatron with ~8T dipoles and moving the old dipoles to the Main Injector tunnel as a second pbar accumulator. This would be done when the Tevatron is turned off for connection of the Main Injector and Tevatron tunnels. Then one could do T-factory physics at $\sqrt{s} \approx 4$ TeV.

This intermediate stage would not compete with the LHC because of the different physics goals. The final stage of a 20 TeV ring does compete with the LHC, but at a much more sensible energy and at a lesser cost. In the light of what could be done at Fermilab, I regard the LHC as too risky and not worthy of support.

II. Cost Savings

1. *p-pbar collisions instead of p-p.*

Magnet production costs would be close to half that of a p-p collider. At Fermilab the pbar source comes for "free".

2. *Existing infrastructure.*

It is very costly to create a new, large national laboratory from scratch. At the same time this was being done in Texas, we were being told that there are too many high energy physics national labs. The cost of a 20 TeV upgrade at Fermilab would only be those incremental costs over and above the present manpower, construction, and operation costs.

3. *An existing Fermilab management team.*

People who had experience with the SSCL have told me that it was costly and inefficient to assemble an inexperienced directorate and bring in outside "managers" to "run" the lab. Fermilab has an experienced management staff and directorate with a good track record. It is very important to let Fermilab run its own upgrade program.

4. *State of Illinois contributions.*

The Illinois site proposal for the SSC pledged $318 million toward tunnel excavation costs in addition to the land procurement costs plus roads and site preparation.(1)

5. *The Fermilab magnet factory.*

Fermilab already has a magnet factory which produced the superconducting magnets used in the present Tevatron and also the SSC dipoles which passed their tests. It seems to me there would be savings in cost and reliability if this factory were enlarged and used to assemble and test the new superconducting magnets. I would recommend a production rate of 500 dipoles per year over 6 years which is about twice the production rate of the existing factory. Costs for the existing 4.5T dipoles were about $40K per magnet including overhead. The new dipoles would be longer but have a 50 mm instead of 75 mm gap. If we assume a factor 4 increase in cost for these 8.7T dipoles, the total cost would be $480 million. SSC magnet costs were estimated as ~$2 billion.(2) For half as many magnets this comes to ~$1 billion which is a factor of two higher than my extrapolation from the Fermilab magnet factory. SSC prototypes for 20 TeV dipoles and for the 9 T HEB dipoles have passed the tests. The 50 mm gap of the SSC magnets is adequate to hold both pbar

and p separated beams in the same magnet because the dynamic aperture is smaller than the physical aperture and it centers on each closed beam rather than on the magnet.(3)

6. Cost summary.

Wm. Foster has a more complete cost estimate derived from SSC figures.(4) He proposes a 10 km radius ring which reaches 20 TeV using 3000 dipoles of 17 m length at 8.5T. He estimates $840M for dipoles, $79M for quads, $35M for straight sections, $628M for tunnel, and $700 for detectors. This totals $3.08B. For a $700M per year total high energy physics budget over 10 years, $300M per year would be for construction and $400M per year for operations.

III. Political considerations

Many of the U.S. congressmen who voted down the SSC have stated that they value the physics and they would like to see that physics done, but at a lower cost. Many of them felt the SSC costs had gotten out of line. Then these congressmen should not object if the new physics can be contained within the "present" U.S. high energy physics budget. However, some of them have said there should be international financing of future large-scale science projects. But this paper is proposing a continuing improvement program of an existing U.S. national laboratory rather than an international laboratory. It is not a new site to be decided upon and staffed from scratch by an international directorate. It would be one more of a series of Fermilab improvement programs. On the other hand, foreign countries will, as usual, contribute to the experimental program in proportion to their participation. Considering the U.S. poor track record, foreign countries would be reluctant to contribute to new, large science projects that are subject to the yearly whims of Congress.

We should not be distracted by the LHC. The 1990 Drell panel concluded that it is at the wrong energy and luminosity. Their report stated:

"The Subpanel has concluded on physics research grounds that any substantial reductions in the energy of the SSC would compromise our ability to elucidate the nature of electroweak symmetry breaking, a truly fundamental problem at the core of the Standard Model. This is because, with 20 TeV/beam, there is confidence that these phenomena can be studied in whichever form they may take, whereas this confidence is quickly lost at lower energies. In addition, no substantial increase of luminosity can make up for a reduction in energy because no multipurpose detector is capable of operating well above 10^{33}, the design luminosity of the SSC."

They are saying that the LHC is too low in energy and too high in luminosity. I agreed then and I agree now and I refuse to support questionable physics even if the Drell Panel should reverse themselves and now say the U.S. should give financial support to the LHC. We can much better use that money in upgrades at Fermilab. We can have 20 TeV colliding beams and 10^{33} luminosity at Fermilab for less than the cost of the LHC! Because of the LHC present magnet and financing difficulties it would take at least 10 years to build it, if ever. Fermilab already has such a head start that it could achieve 20 TeV colliding beams within 10 years and at lower cost than the LHC. Physicists should only lend their support to good physics. It certainly would be a grave mistake for the Drell subpanel to encourage support of the LHC in place of Fermilab in order to achieve the physics that we already have agreed upon as the most important. If HEPAP ends up choosing LHC over Fermilab, they will lose support of much of the U.S. high energy physics community.

Another possible way to produce Higgs particles would be e^+-e^- collisions in the TeV range using colliding linacs. So far the technology does not exist and neither do cost estimates (except to say that the RF is very expensive). It should be emphasized that the Tevatron upgrades proposed here utililize existing technology capable of giving reliable cost estimates. It would be foolish for the Drell subpanel to give up on the sure way to achieve this energy region in hopes that some day perhaps it could be done by linear colliders. Howerver, I do endorse a moderate level of linear collider research.

IV. Phasing

A big advantage of doing 20 TeV physics at Fermilab is that there can be an intermediate stage where other important physics can be done earlier and with less expense. A total of 3000 dipoles would be needed for the new ring. The first 300 of these (or a similar design) could be used as replacements for the present Tevatron magnets.(5) This would permit Tevatron operation at about twice the present energy within 5 years. Then we could be doing t-quark physics while the 20 TeV ring is under construction. Much important physics has resulted from the study of b-quarks. A fringe benefit of this is that a second pbar accumulator (called the Depository) could be assembled almost for free in the Main Injector tunnel by using half of the old Tevatron magnets. As discussed in the next section, this could boost antiprotons per bunch by a factor of 7 or so. Also the Tevatron would inject at 2 TeV rather than 1 TeV into the 20 TeV ring which makes the 20 TeV magnets easier and cheaper to build.

Bill Foster has proposed a different path to the T-factory.(4) He would fill the 20 TeV tunnel with the first 600 of the 3000 magnets and connect them with 2840 straight sections at an additional cost of $192M. But for less cost one could refill the Tevatron tunnel as

proposed above. The advantages of using the Tevatron tunnel rather than the 20 TeV tunnel for a T-factory are: (1) less cost, (2) we get a higher energy injector for the 20 TeV ring, (3) we get the pbar Depository, (4) the 20 TeV tunnel would not be tied down so that magnets could be installed as they are completed, and (5) less time lost to shutdowns.

V. Luminosity

The luminosity of the 1 TeV Tevatron after the Main Injector improvement is expected to be $1 \times 10^{32}\ cm^{-2}s^{-1}$.[6] With this as a starting point, I will try to extrapolate to a 20 TeV ring. The formula for luminosity is

$$L = \frac{N_p N_{\bar{p}} f}{4\pi\sigma^2}$$

where N_p is number of protons per bunch and f is number of bunches per sec.

The ratio of luminosities for two different rings is

$$L'/L = \frac{(N_{\bar{p}} f)'}{(N_{\bar{p}} f)} \times \frac{\gamma'}{\gamma} \times \frac{\beta}{\beta'}$$

where σ^2 has been replaced by $\varepsilon_0\beta/\gamma$ and both rings have the same N_p.

Now replace $(N_{\bar{p}} f)$ with $n_{\bar{p}}$ where $n_{\bar{p}}$ is the total pbars in the ring.

If all the pbars in the Tevatron are injected into the 20 TeV ring

$$L'/L = \frac{\gamma'}{\gamma} \times \frac{\beta}{\beta'}$$

The Tevatron is proposing $\beta = 0.25$ m while the SSC needed $\beta = 0.5$ m. Then $L'/L = 21.3 \times 0.5 = 10.6$ or $L' = 10^{33}$ which was the SSC goal.

This value of 10^{33} is for luminosity just after filling and assuming no pbar Depository in the Main Injector ring. But because of radiation damping this value would increase by ~60% over the first 20 hours. Fig. 1 shows that it would take 50 hours to drop back down to its starting value. The average boost in luminosity over 50 hours is a factor of 1.35 . The fact that radiation damping causes the luminosity to stay high for ~50 hours can boost the luminosity by another factor of 5 once the pbar Depository is built. Without the Depository the number of pbars in the Accumulator would saturate after about 10 hours of pbar production.[7] But with the Depository there would be no saturation and one could keep producing pbars for 50 hours. So this is an additional factor of 5 in luminosity. Also, at the

end of a store the remaining in the 20 TeV ring could be deaccelerated and put back into the Depository with a further factor of 1.5 increase in luminosity. There is a very significant gain in combining these three factors: (1) use pbar-p, (2) work above the radiation damping threshold, (3) use a pbar Depository in an existing tunnel with existing magnets. So far we have discussed extra luminosity factors of 1.35, 5, and 1.5 (a combined safety factor of 10.1 more than the luminosity of 10^{33} that was estimated in the previous paragraph). In addition to all this there is an existing project for bunched beam stochastic cooling in the Tevatron ring which might give another factor of two and which can also extend the length of the store time.[7]

VI. Conclusions

Construction should start soon on a new Fermilab tunnel 63 km in circumference. R&D should start soon on dipole magnets capable of 8.5T corresponding to stored beam of 20 TeV. (Such prototypes for the SSC High Energy Booster have already been built and tested.) Pbar-p collisions should be used rather than p-p for three reasons: (a) half as many magnets would be needed with considerable cost saving, (b) radiation damping combined with an inexpensive pbar Depository gives a factor of 10 boost in luminosity compared to a factor of 1.3 for p-p, (c) Fermilab already has an excellent source of antiprotons. At the time that 300 new dipoles have been fabricated they should be installed in the Tevatron ring in order to permit 2 TeV x 2 TeV physics to start up. The technology for everything proposed here already exists; whereas the technology for colliding linacs above the Higgs threshold does not exist. U.S. money should not be spent on the LHC; it can much better be used on Fermilab upgrades.

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References

1. "Siting the SSC at Fermilab - An Independent Cost Study", A.T. Kearney, Inc., Feb. 12, 1988.
2. "Report on the SSC Cost and Schedule Baseline", DOE/ER-0468P (1991).
3. R. Talman, private communication.
4. G. William Foster, "A staged resurrection of the supercollider at FNAL", 24 Jan. 1994, a working paper for the FNAL Long Range Options Group II.
5.G. Jackson has calculated that a 5 cm gap would be adequate for these magnets.
6. Report of the FNAL Future Options Group, "New Accelerator Directions", Jan. 28, 1994.

7. G. Jackson, private communication. Once the Main Injector is completed the pbar stacking rate is expected to be 15 mA per hour. There would be 150 mA of storage space in the Accumulator. So after 10 hours the Accumulator would be full.

Fig. 1 Fig. 5.2.2 from p. 48 of "Site-Specific Conceptual Design Executive Summary", SSCL, July 1990.

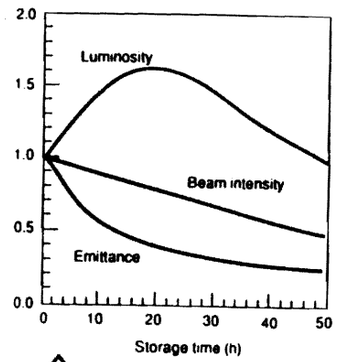

Figure 5.2.2 Collider luminosity, beam intensity, and emittance as a function of time for the parameters given in Table 5.2.1. The value of 1.0 on this scale corresponds to the design values (10^{33} cm^{-2} sec^{-1} luminosity).

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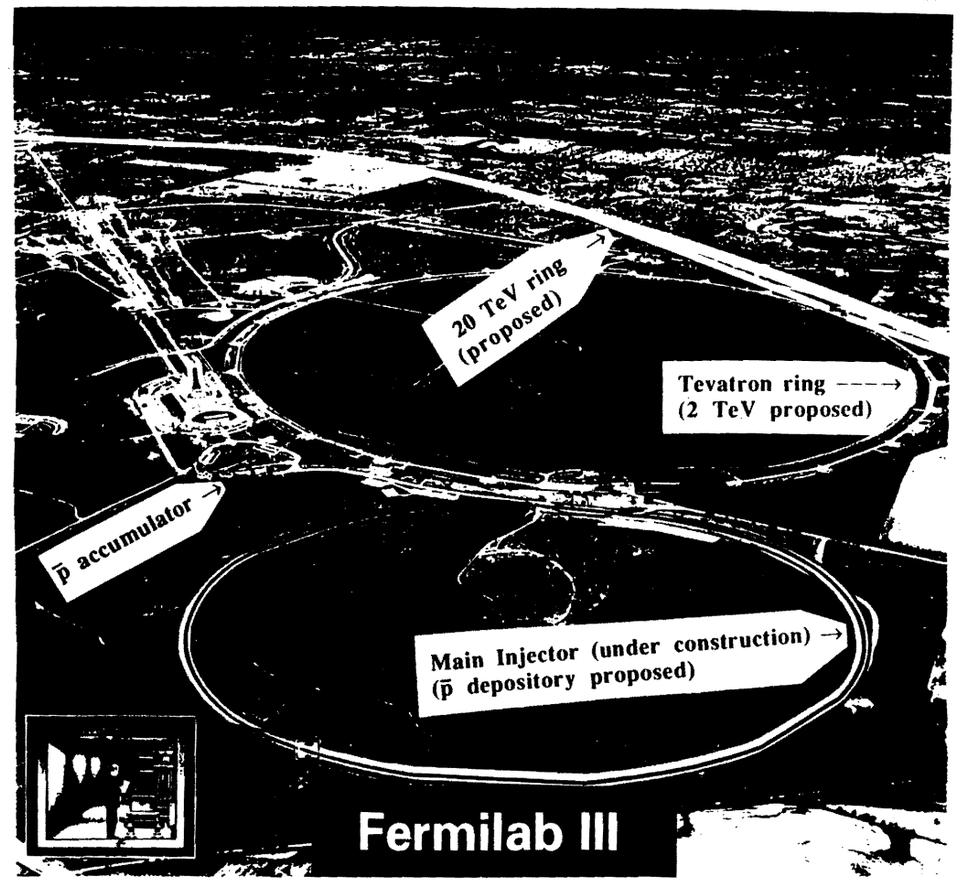
Fig. 2 Site photo with artist rendering of the Main Injector and part of the 20 TeV ring.