New Technologies for a Future Superconducting Proton Collider at Fermilab

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I. SUMMARY

New innovative approaches are required to continue the dramatic rise in collider energies represented by the well-known Livingston plot. A large hadron collider can be built either with high field or low field bending magnets. The low-field approach, sometimes called the "Pipetron," in many respects resembles a pipe in the ground carrying protons.

This old idea [1] of low-cost, low-field iron dominated magnets in a small diameter pipe was not pursued a decade ago because at the time, there did not appear to be a cost advantage (measured in cost/TeV) over the high field (Tevatron, SSC, LHC) approach. The low-field approach is now receiving a fresh look. Such a machine could become feasible in the next decade because of dramatic recent advances in technology:

- Advanced tunneling technologies for small diameter
- Remote guidance for tunnel boring machine steering
- High T_C-superconductors (HTS)
- Industrial robotics and remote manipulation
- Digitally multiplexed electronics to minimize cables
- Achievement of high luminosities in hadron colliders

There is an opportunity for mutually beneficial partnerships with the commercial sector to develop some of the necessary technology. This will gain public support for the undertaking, a necessary part of the challenge of building a new, very high energy collider. Low cost, measured in $/TeV is the <u>essential</u> motivating factor.

Because of new technologies available now or in the foreseeable future this <u>new</u> Pipetron looks very different than the old "sewertron" idea. Work at Fermilab on the "new" Pipetron began in Nov. 1995 with weekly meetings held in the Technical Division's conference room. Work by the many people excited by the concept was presented and discussed.

An important step was the mini-symposium "New low-cost approaches to high energy hadron colliders at Fermilab" at the May 3, 1996 APS Annual Meeting [2]. This full-day meeting prepared our rapidly growing group for Snowmass 96. This paper describes work done on the "Pipetron" prior, during and subsequent to Snowmass 96. Current work is posted on the web: **http://www-ap.fnal.gov/PIPE/**

II. ORGANIZATION AT SNOWMASS

We organized ourselves into 6 teams:

- Physics/Detector Team,
  Dima Denisov & Stephane Keller, co-leaders
- Accelerator Dynamics and Parameter Team
- Magnet and Vacuum System Team, Bill Foster, leader
- Cryogenics and Power Supply Team,
  Peter Mazur & Mike McAshan, co-leaders
- Tunneling/Accelerator Enclosure Team, Joe Lach, leader
- Beam Loss and Radiation Issues Team

These teams met individually or collectively. Several joint meetings were held with the group exploring the high-field RHLC. In addition, many useful conversations took place at the Pipetron Hospitality Suite, sponsored by *Electronic Theater Controls, Inc*., open from 5:30 - 7 PM during eight evenings of the Workshop.

III. PHYSICS and DETECTOR ISSUES

The physics justification for building a hadron collider with ≥ 50 TeV/beam is covered in several papers in these proceedings [3]. Clearly much more work is needed. A personal opinion: although the physics is independent of the collider magnetic field, many people, especially young scientists who were disheartened by the SSC failure, are excited by the Pipetron concept, viewed as having a hope of becoming affordable and buildable during their productive lifetimes. Several are working on physics/detector issues that don't depend on high-field or low-field, but are motivated by the low-field concept. A Workshop on Physics and Detector Issues is being organized to be held at Fermilab in Spring 1997.

Denisov [4] has defined some of the issues for a high p_t general purpose detector for a 100 - 200 TeV cm pp collider with luminosities of 10^{34} or more. He concludes that calorimetry looks reasonable; one of the more promising approaches is high pressure gas calorimetry, partly because of the high radiation environment at the IP. Tracking and muon detection are difficult; interactions per crossing »1 deteriorate detector performance significantly. R&D on detector technologies is needed; this should be motivated as much as is the accelerator R&D by a search for new low-cost innovations.

In discussing energy and luminosity it is useful to look at recent history. The Tevatron Collider design luminosity was 10^{30}. Operations began in 1983; 13 years later, the luminosity had climbed a factor of 20 over the design. The TeV33 project envisions another factor of 50 several years from now. Accelerators and detectors have undergone and will continue to undergo substantial upgrades over this 20 year period. One could anticipate a similar evolution of the Pipetron. It could come on at 10^{33}, and at that luminosity do initial explorations. Perhaps after 5 years it would reach 10^{34} and run there for several more years. With results from these runs, after a decade or so an upgrade path beyond 10^{34} might evolve including new or substantially rebuilt detectors and beam abort systems. These upgrades would be based on the physics learned and the state of technology at that time.

IV. ACCELERATOR PHYSICS

One of the most serious Pipetron issues is emittance growth driven by noise. This noise spectrum rises as 1/f at low frequencies. There are two approaches to this problem; both must be investigated:

- Passive suppression of emittance growth by mechanically mounting the magnets to isolate them from sources of rapid motion and/or cryogenic/electrical system design eliminating sources of noise.
- Active suppression using feedback requires extremely low noise pickups and preamplifiers and damping times that are short compared to the decoherence times.

Problems of emittance growth due to noise have been systematically studied in the Tevatron and sources of growth eliminated or reduced in importance. Even though its circumference is 1/160th of the "ultimate" Pipetron, experiments in the Tevatron can be used to verify calculations and test feedback schemes. Recent work by V. Shiltsev [5] reaches the following conclusion: "A transverse and, probably, a longitudinal feedback system are necessary for emittance preservation, and sophisticated beam-based orbit correction methods should be used at the Pipetron. We observe no unreasonable requirements which represent an impenetrable barrier to the project."

Transverse stability issues arise from the large circumference and the room temperature, relatively high resistance aluminum vacuum chamber. TMCI, the transverse mode coupling instability, a single bunch problem, and the coupled bunch resistive wall transverse instability were discussed during Snowmass [6,7,8]. TMCI will limit the "ultimate" luminosity of the collider and the coupled bunch problem will require a sophisticated feedback system.

An initial look at TMCI parameters at Snowmass resulted in increasing the magnet aperture [9] from 15 to 20 mm, ID 13 to 18 mm. This gives an impedance of 119 MΩ/m. The TMCI threshold depends on several parameters. One of them is injection energy. A "Snowmass RLHC Parameter Set" [10] uses 3 TeV. At a luminosity of 10^{34}, RF voltage 200 MV, RF frequency 1.7 GHz, and every 1/10 bucket filled with charge, the TMCI threshold is 960 MΩ/m, giving a comfortable safety factor; however, this bunch spacing may be too short for other reasons. At 10^{35}, the threshold drops to 303 MΩ/m, which is uncomfortable since the impedance of BPM's and RF cavities has not yet been included. One could increase the magnet aperture more. Another solution is to divide the charge at injection into more buckets, and then coalesce them part way up the ramp. Clearly more work is needed, both on the magnet prototype effort, and on developing a consistent set of Pipetron parameters.

It should be emphasized [11] that the TMCI formulas used are only approximate. It would be useful to carry out an accelerator experiment in the Tevatron where the transverse impedance is artificially increased to try and observe this single bunch instability.

On our plate for 1997 is to develop a consistent set of Pipetron parameters. Effort has already begun in that direction [12]. Assuming we fill the 3 TeV ring from the 150 GeV Main Injector, and that this intermediate ring uses Pipetron technology, it seems logical to have the "ultimate" Pipetron reach 60 TeV. So the working paramters at this point are 60 TeV, 90% packing factor, 2.0 T max field, for a circumference ~ 700 km, assumed in the TMCI estimates given above. In the final analysis the energy will be determined by cost/TeV and what is affordable to the nation and the international community that builds the RHLC [13]. A 64 TeV/beam collider could fit in Illinois, whereas higher energies will cross state boundaries, possibly an advantage politically.

V. MAGNET

The key element in a new large hadron collider is the magnet. A promising candidate for the magnet is the "double-C twin bore transmission line magnet" proposed by G. W. Foster [9]. A 3-D rendering of it is shown in two recent overviews of the Pipetron [14, 15]. A single turn magnet carries 75 kA to excite twin 20 mm apertures. The design is warm iron, warm bore. The cold mass is small and cool down will be fast. The warm-bore C-magnet has a number of well-known advantages: the field can be mapped prior to beam pipe installation, there is access to magnet pole tips for shimming/trimming/survey and to the vacuum system, BPM's etc., without disturbing the cryogenics. The vacuum system can be easily installed in long lengths into a C-magnet. It is now possible to obtain solid low-carbon steel extrusions with good tolerances in long lengths, consistent with the current design. ANSYS calculations of eddy currents indicate laminations are unnecessary for a machine with 5-20 minute ramp [16].

Alternating gradient pole tips (no quadrupoles) allow the drive conductor, vacuum system, and iron to be in long lengths, minimizing end costs. Long, identical modules make installation and repair easier. Our current parameter choice is Neuffer's [12] half-cell length, 250 m, phase advance/cell, 60^o. An innovative idea for the harmonic correctors is to use the same high current drive to energize various shaped blocks of iron moved with stepping motors.

The Pipetron "transmission-line" cryostat has many similarities to superconducting power transmission lines. Development of this magnet type parallels ongoing industrial development of HTS Power Transmission Lines which will come to fruition in this decade. Although the beam sees 2 T. the conductor sees $\leq$ 1 T. Presently commercially available high T_c conductors can carry the current density required if the coil is cooled to 20 K. Conductors under development may carry this current at 77 K. Due to the symmetry of the design there are no unbalanced forces on the conductor. This simplifies the cold mass support ("spiders") and allows a low heat leak design.

A demonstration/test facility is now under construction as a joint project of the Fermilab Technical and Beams Divisions. The prototype test setup uses a single 60 kA current loop, and will provide 2 T field in two 15 mm magnet gaps. To avoid high current cryogenic leads the current loop is driven as a shorted single turn secondary winding on a transformer built from an old accelerator magnet.

The goals of this facility are to demonstrate the concept using helium cooled surplus SSC conductor and provide a test bed for field quality demonstration and pole tip development. From Foster's work done at Snowmass [9] it appears that crenellations are necessary to achieve good field quality in a gradient pole tip up to 2.0 T. This can be modeled in a 2-D program but experimental verification is necessary. Work has only begun on specifying the field quality required [17,18].

The test facility will allow an eventual upgrade to high-Tc conductor. High temperature superconductors (HTS) are a key technology today that was not available to the SSC or LHC. Multi-filamentary BSCCO conductors are commercially available now; BSCCO-2212 and BSCCO-2223 when they are operated at <20K offer enormous capability. Their current carrying capacity is high and rather independent of field [19].

Commercially available conductor for use in LN_2 cooled transmission lines is getting better all the time. A liquid nitrogen cryogenic system is *much* cheaper than helium and even more so if the helium is at 1.8 K. Liquid hydrogen is also an attractive possibility [20]. Another interesting possibility presented at Snowmass is the use of Nb_3Sn running in cold He gas [21].

Piping in the tunnel is also substantially cheaper for the HTS cryofluids. Hydrogen has a latent heat of 450 joules/gram, 22 x that of helium. Consequently, flow rates required for the same heat leak are smaller and the pipe sizes required in the main transfer line in the collider enclosure are considerably smaller resulting in substantial cost reductions.

VI. VACUUM SYSTEM

The vacuum system design [22] has the features of low cost and high reliability. Continuous aluminum extrusions obtained in long lengths, ≥250 m, are periodically anchored to the iron to control thermal effects. One of the key design features is to have <u>no</u> bellows. Finite element analysis has shown that this system will work. The oval chamber is variable thickness, 1.0 mm thick top and bottom which is what determines the vertical impedance.

A high-conductance side chamber for pump down contains the distributed non-evaporable getter (NEG) pump, a standard solution for electron machines. An outgassing rate of approximately 10^{-13} Torr-liters/sec/cm^2 can be achieved utilizing chemical cleaning at 70^{o}C, and a one hour mild baking at 350^{o}C during NEG strip activation.

In the center of each 250 m (at β_{max}) will be the x-y beam position monitor (BPM), lumped ion pumps for pumping noble gasses, a roughing port, and the NEG strip power feedthrus. At the end of each 1000 m magnet will be placed a quick disconnect, and a gate valve. The magnet can be built and inserted into the accelerator enclosure under vacuum.

Synchrotron radiation plays a minor role in the Pipetron compared to the high field, very high energy case. The synchrotron power radiated is 0.13 watts/meter (at 10^{34}), relatively weak compared to contemporary electron rings. This has both advantages and disadvantages [23]. The decrease in photon intensity in the Pipetron compared to electron storage rings is compensated by a slower cleanup rate for the vacuum system, so similar linear pumping speeds are required. A major problem is methane which is not pumped by the NEG strips. This may require distributed ion pumps. There appear to be large safety margins for ion desorption stability and beam induced multipactoring. Beam lifetime calculations due to multiple scattering [24] will need to be reviewed once we converge on a parameter list. However, it is already clear for the range of parameters considered that transverse scattering effects are probably going to be small. Scattering affects predominately the longitudinal plane and through the bunch length the luminosity.

VII. CRYOGENICS

Cryogenics baseline parameters [21] are based on NbTi. Inside the enclosure will be three lines for the cryogenic system: the drive conductor line in the magnet, the main liquid cryogenic transfer line, and a warm gas return line used for cooldown and quench recovery. The length of one cryogenic loop is 38 km, requiring a building and refrigeration plant every 76 km. The total heat leak budget is 300 mW/m (for magnet and return). A recooler is placed every 840 m. Assuming a heat leak of 100 mW/meter is attained in the transmission line structure, the temperature rises from 4.55 K to 5.0 K between recoolers. Total cryogenics wall power requirements are given in ref. [21] for various cases. If LN_2 cooled HTS becomes feasible these power requirements will be significantly less.

The type of superconductor (LTS or HTS) is not yet determined so a universal quench protection approach [25] that depends only weakly on the critical temperature of the cryogen is used. The superconductor is in good electrical contact with cable copper area of 1.8 cm^2. The design of the quench system/power supply system is mainly driven by the allowable peak temperature, assumed to be 500 K, and the peak voltage to ground, assumed to be $\pm$2 kV. Kephart [26] has developed a promising concept for a cryostable transmission line that merits further investigation.

Power supplies and switched series resistors are evenly spaced to minimize voltage to ground. The 38 km loops assumed for the cryogenic (helium based) system are also reasonable for the power supplies and dump resistors.

VIII. GEOLOGY AND HYDROLOGY

Bauer and Gross [27] have described the suitability of the Fermilab site and region around it for a new large collider project. In an informal talk given by J. Peoples at Snowmass 96, the suitability of the Fermilab site for the next new accelerator project was emphasized.

Site conditions at Fermilab are well understood. The Illinois State Geological Survey (ISGS) has extensive data on the regions under consideration from several hundred-thousand drill holes, and additional data compiled when there was active consideration given to siting the SSC in Illinois.

Neighboring mid-West states have similar extensive information relevant to a large project of this sort.

There are predictable rock and tunneling conditions, relatively homogenous rock mass, seismically stable with no movement in recorded history. There is a vibration free environment, important to minimize emittance growth problems. There are no settlement problems at the depths being considered.

Even the largest ring considered, 1000 km in circumference is still in glaciated terrain. The dolomite layers under Chicago and under Fermilab are quite uniform. The large regional extent of dolomite can serve as an excellent host for a tunnel or horizontal drill hole in the Fermilab region.

In a glaciated region, groundwater is typically present in the glacial drift and in the uppermost few meters of bedrock. In the bedrock beneath Fermilab, the rate of movement of groundwater varies by three orders of magnitude, from 1,000 ft/year in the aquifers to only 1 ft/year in the dolomite layer 100 m below the surface of Fermilab. Therefore, again, this layer is an excellent host for the tunnel.

IX. TRENCHLESS TECHNOLOGY

On July 1, 1996 twelve of us from the "ad hoc" Pipetron working group drove to the Colorado School of Mines Tunneling Laboratory in Golden, CO. Our hosts were faculty members Tibor G. Rozgonyi, Levent Ozdemir, and James E. Friant. This visit and the report [28] of the Accelerator/Enclosure Team significantly altered our pre-Snowmass thinking about the project.

Today the minimum in the cost/foot vs. diameter curve is at $1000/foot and 14 ft. The industry is evolving towards a combination of microtunneling (non-manned entry) and standard tunnel boring (manned entry). With R&D over the next 2-3 years, specifically taking into account the excellent geology in the Fermilab region, the cost minimum could be moved to $300/foot and 8 ft diameter.

The goals of a tunneling R&D program are to

- increase distances between shafts
- develop an "umbrella" machine which "unfolds" at the cutting face allowing remote cutter changing
- utilize remote liner installation methods
- develop long-distance muck removal strategies
- develop guidance for tunneling in a gentle curve and following the terrain to stay in the optimal geology

In order to interact more closely with the Trenchless industry Fermilab has joined the North American Society for Trenchless Technology which represents this rapidly growing multi-billion dollar industry. Trenchless Technology is growing in importance as a practical solution to expansion and repair of underground utilities. This is an area where not only can the Pipetron benefit from the expanding technologies but can also be a catalyst to this environmentally crucial industry.

Robotics (more correctly remote handling) are now being used for repair of sewer pipes ranging from 8 to 30 inch in diameter with access every 300 - 400 ft via manhole. The robots cut holes, put in patches, cut roots out, install new lateral connections, etc. This is another rapidly expanding industry. Remote operations can benefit by the use of virtual reality. Some work has also occurred at Fermilab. Visual Robotic Welding has been developed to repair our beam pipes [29]. At Snowmass interesting concepts were developed [30, 31] for working inside an 8 ft diam tunnel, although our original idea of 4 - 6 ft has not yet been dropped. A high degree of remote manipulation would be used, but people will still be able to go in to deal with unusual occurrences. Alignment is clearly an area that would benefit from automation. With magnet supports every 5 m, and 3 degrees of freedom on each, one could have over 500,000 adjustments to make. The operations challenge will be to learn a new way of working on accelerators with increased emphasis on reliability, redundancy, and fault tolerance.

As discussed above, a first look at cryogenics and power supply/quench protection requirements indicates that an access shaft and surface building will be required every 75 - 80 km around the ring. Depending on evolution in the tunneling/boring industries and detailed cost optimization not yet done, additional accesses to the surface may be required. Clearly the fewer of these the better. Some of these additional access shafts may not be for human access, but would be bore holes for surveying, or running cables of various kinds down to the enclosure.

X. BEAM HANDLING & RADIATION ISSUES

A large on-site straight section will contain most functions requiring frequent human intervention and nearby above ground service buildings. In the straight section will be staging areas for assembly and installation of magnet modules, (one of) the detector(s), the beam abort system, RF, etc.

A preliminary IP design was developed at Snowmass [32]. The IP will use state-of-the-art high gradient quadrupoles ($\geq$ 225 T/m). High field dipoles will be needed to provide the crossing angle and to separate the beams sufficiently where they go through the RF cavities. The challenging problem of beam abort was investigated by Mokhov et al [33, 34]. Whereas kicking the beams out of the tunnel towards the absorbers seems reasonable, the absorber itself is very challenging. Sweeper magnets must spread the beam out over the face of the absorber. Reliability is at a premium since a failure of this system can destroy part of the machine.

XI. AN ELECTRON OPTION

Given a very large radius of curvature enclosure, one may well ask, if, in the CERN tradition of LEP/LHC, one couldn't put an e^+e^- collider in the same pipe. This is an interesting idea that needs discussion. Simple minded E^4/R scaling from LEP allows an e^+e^- collider in the pipetron enclosure to be above the $t\ \bar{t}$ and possibly Higgs threshold for the same total RF voltage as LEP II. The required dipole strength is < 100 Gauss [35].

XII. NEXT STEPS AND CONCLUSIONS

This project was conceived with the aim of pushing the energy frontier a factor of 100 further than it is today. It will rely for its success on synergy between this physics goal and the economic and environmental goals of the trenchless technology, superconducting power transmission, and industrial robotics industries.

The next steps are to work in parallel on the main issues: the physics case and preliminary detector parameters, accelerator parameters, lattice, and dynamics, R&D on magnets including the use of HTS, and together with industry work on tunneling and robotics.

To gain public support two things are important. The cost, measured in $/TeV must be significantly lower than other projects, and also in absolute terms must be a reasonable amount. A very preliminary look at the major cost drivers (quantities of superconductor, mass of the magnet, complexity, vacuum system, collider enclosure volume, stored energy etc.) give rise to optimism that this goal is achievable. Both capital and operating costs are important. Also, there must be real benefits to society from the R&D leading to this project and also in its execution.

The benefits from developing technology which allows one to decommission high-voltage surface power lines, and replace them with underground robotically tunneled and maintained HTS transmission lines, are obvious. Other benefits might include shared use of the collider enclosure for infrastructure. The capabilities developed may open new markets for the private sector. Study and hard work over the next few years will determine if the Pipetron meets these criteria.

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