62-TeV Center of Mass Hadron Collider with Superbunch Beams

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Abstract:

The scheme of a 62-TeV center of mass p-p collider with superbunch beams at Fermilab is proposed as a practical and realistically achievable future project. It will be built in two stages, using the same tunnel, first with a 2 Tesla low field magnet collider ring and later with a 10 Tesla high field magnet collider ring. Both low and high field magnets have twin bore aperture and will be installed in the tunnel with the circumference of 87.25 km. In each bore a proton beam is accelerated, using induction cavities to increase luminosity. In the first stage we install a 7 TeV accelerator ring with operating field of 2 Tesla, based on the superferric transmission-line design. This ring will be operated as a 14-TeV center of mass collider. This will have the same energy as the LHC, but it will have 15 times higher luminosity, namely 1.5 x 10^{35}/cm^2/sec. The estimated synchrotron radiation is negligible with this machine. The existing Fermilab accelerator system, including the 150 GeV main injector, will be used as the injector system. Its rough cost estimation and schedule for this first stage are presented. In the second stage proton beams are accelerated, also using induction cavities up to 31 TeV with the10 Tesla dipole magnets. The counter circulating beams will collide with the 62-TeV center of mass energy. With the superbunch beams we can expect the luminosity can be increased about 15 times more than the conventional method with RF cavities. It will be 10^{35}/cm^2/sec. In the second stage, the synchrotron radiation power will be about 12 W/m, and we need an elaborated beam screen.

In appendix another hadron collider up to 90 to 100 TeV center energy is attached.

1. Introduction

As a future project in high energy physics, the VLHC has been proposed for the future hadron collider in USA. The LHC, 14-TeV center of mass hadron collider is being constructed now at CERN, and probably will be in operation in 2006 [1]. We should consider building a hadron collider, which eventually surpass the energy of the LHC, but it should be realistically conceived as a realizable machine, budgetwise, spacewise, and timewise. The scale of the collider should be in the range, which can be manufactured by the industry in a reasonable time, and with an affordable cost. The machine should be designed also as a maintainable machine with present-day's technology. In this vein, as one variant of the VLHC, the 25-30 TeV P-P collider with two-stages using a same

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tunnel was proposed [2]. Presently a VLHC for the energy range of 175 TeV with much higher intensity is proposed [3].

Recently a series of proposals of applying induction acceleration method to the circulating synchrotron has been made [4]. Its application to a hadron collider is also proposed, with possible increase of the luminosity about 15 times over the RF cavity acceleration [5]. We apply this induction acceleration method to our present design of the 62-TeV center of mass hadron collider in both stages.

2. General Descriptions

This collider complex will be based at Fermilab site, and will be built in two stages, utilizing a same tunnel with 87.25 km circumference. The basic parameters of this hadron collider are given in Table I. The Fermi Main Injector of 150 GeV proton beams will be used as the injector to the first stage. In the first stage the 14-TeV center of mass hadron collider will be installed using 2 Tesla superferric magnets. Its accelerator scheme is similar to the one described for the 175 TeV VLHC proposal [6], except the circumference size of the tunnel and its beam acceleration system. The beams will be accelerated to 7 TeV with accelerating induction cells and barrier bucket induction cells to produce superbunch beams [4,5]. At this energy the synchrotron radiation loss is negligible, so we use 114 superbunch beams of 300 meter long. The maximum center of mass colliding energy will be 14-TeV with the expected luminosity of 1.5 $x10^{35}$ $/cm^2/sec$. This will be used for high energy experiments with two detectors.

In the second stage we will use the twin-aperture 10 Tesla superconducting magnets. The operational dipole magnetic field of 10 Tesla using Nb_3Sn conductor, is achievable with the present technology. The maximum accelerated proton energy will be 31 TeV, resulting in the center of mass energy of 62-TeV. In this second stage, the application of Superbunch beams is being studied to get the expected luminosity of $5x10^{34}/cm^2/sec$ without generating too much synchrotron radiation loss. To reduce the synchrotron radiation loss below the acceptable level, the number of the superbunch beams is reduced to 26 and their beam length are shortened to 150 meter long each.

In both low and high field magnet rings, we use the twin bored magnets, with two bores separated horizontally. For the beam stability, we have to use the horizontal beam crossing at one intersection and we have to rotate both ribbon-shaped beams by 90 degrees and cross beams vertically in the other straight section [5].

3. Tunnel

The tunnel will be placed at a depth of 130 meters from the surface, and will be built to minimally affect the environment on the surface. The 62-TeV collider has the total circumference of 87.25 kilometers, and we have to add several access shafts around the circumference. The cost of the tunnel could be estimated about one billion dollars, based on the estimated cost of 2.125 billion dollars for the tunnel with the circumference of 233 km [3], considering the enlarged tunnel cross section and the transit system.

The overall layout of the 87.25 kilometer tunnel is shown in Fig.1, and the expanded view of the Fermilab site is shown in Fig.2. Inside the Fermilab site there will be two major long straight sections, where two major 62-TeV hadron collider detectors will be installed. The collision halls will be 200 meter long. These two detectors will be used for the collider experiments with the 14-TeV center of mass energy in the first stage in the same locations. In the second stage, the low field ring in the long straight sections will be moved into an outward bypass.

In addition to two long straight sections, there will be three utility straight sections in the Fermilab site. Two utility straight sections will be used for the injection from the Main Injector to the low field magnet ring in both directions, and also used for transferring two proton beams from the low field magnet ring to the high field magnet ring. The induction cavities and the liquid Helium connection will be placed in the central1km long straight section. The abort lines will share partly the outward bypass line. On the other side of the tunnel, there will be two 1km long straight sections and three short utility straight sections for future usage.

The cross section of the tunnel for the 14-TeV collider is shown in Figure 3. In the second stage, the low field ring will be lifted up by 2 meters to make room for the high field magnet ring, as shown in Fig.4. The high field superconducting magnet for the 62-TeV collider is shown together with the magnet of the 14-TeV collider ring. A cryogenic pipeline for transporting liquid helium is also shown. To implement excellent maintenance of these colliders, the radius of the tunnel cross section is chosen to be 3 meters. It is imperative to have a fast transit system to be installed inside the tunnel for transportation of personnel as well as for moving parts.

4. High Field Magnet

The development of 2 Tesla low field magnets at Fermilab is reported in the VLHC report [6]. The high field magnets are extensively being developed at several institutions in the world, including at Fermilab, as reported in the VLHC report [7]. The superconducting material, which is being utilized for this high field region is Nb_3Sn. The highest field achieved in short magnets of this type is 13.5 Tesla at LBNL [8]. Another short magnet developed at University of Twente with Nb_3Sn, obtained 11 Tesla [9].

Recently we reported the design and problems of the long Nb_3Sn magnet [10]. We stressed the importance of the extensive use of the quench heaters for long high field magnets, as is done with the LHC magnets. Also we stressed an extensive study is needed for the thermal stress analysis and the resulting deformation in the epoxy impregnated Nb3Sn coil after a quench [11]. We expect the epoxy impregnated coil in long high filed magnets experience temperature surge above 300 K in a very short time.

There are other several technical problems to be solved for the development of long high field Nb_3Sn superconducting magnets. First the useable aperture of the magnet should be determined. This requires detailed and extensive study of dynamic aperture from the accelerator requirements using detailed field quality of the magnets. Also the mechanical structure of a synchrotron radiation shield in the beam bore should be studied, because it will practically defines the aperture size.

Secondly, the persistent current in the superconductor cable largely affects the field distribution at the injection time. Presently the effective filament diameter size d_{eff} of the Nb_3Sn superconductor strands is about 100 and 150 microns, generating a quite large sextupole field component at the injection field of 2 Tesla. Some recently developed conductor has a d_{eff} value about 50 microns. We hope this value will be reduced further down in a few years.

Thirdly, we need superconductor with a high current density above 2500 A/mm^2 at 12 Tesla and 4.2 K. This value seems practically available from industry in a few years. We need an extensive development on the side of superconductor manufacturers. With the industry's rapid trend, we should be able to get good superconductor in a few years.

5. Induction Cell Acceleration System

With the induction cell acceleration, the acceleration and longitudinal focusing are independently achieved. It allows ultimate use of longitudinal phase-space and is quite effective to substantially increase the beam intensity in synchrotrons [4]. We need two types of induction cells for this system, one for the acceleration induction cells, called A-IC, and the other for the barrier bucket induction cells, called BB-IC. These induction cells are now being developed intensively at KEK [12].

5.1. Design and Coreloss of Acceleration Induction Cell

With the circumference of 87.25 km, it takes 291 μsec to go around the ring. It is not necessary to have an induction cell, which operates that long. We divide the circumference into N units and repeat the operation N times to do the job. In the first stage we divide the circumference into 114 units, 765 meter long each. The bunch spacing is 2.55 μsec. To make a 0.9 μsec composite long acceleration pulse, a unit induction cell is made of two sets of cores, each generating a 0.45 μsec pulse in succession. At both ends of this 0.9 μsec accelerating pulse, there are barrier bucket pulses with different polarity. And in the following 1.5 μsec, all induction cores are reset. These cores are triggered by high current semiconductor switches, which can be operated precisely and reliably [12]. We use 114 and 26 superbunch beams for the first and second stages respectively.

A set of four FINEMET FT-3M cores [13], each with dimensions of ID=10cm, OD=50 cm and width=1cm, is used to generate a 2.5 kV pulse with 0.45 μs pulse width. Two sets of cores will be used as a unit induction cell for the first stage, and only one set for the second stage.

The coreloss for unit induction cells are 4 kW and 0.45kW, and the maximum total peak coreloss per beam will be 1.7 and 0.52 MW for the first and second stages respectively. The total coreloss for the second stage is lower, because the number of the superbunch beams is reduced due to the excessive synchrotron radiation loss. The cooling of cores is a challenging job, but can be done.

5.2. Voltage of Barrier Bucket induction Cells

The necessary voltage V_{bb} of a barrier bucket induction cell with half sine waveform, is given by the following equation,

$$V_{bb} = (\pi/4e)\,(T_0/T_{bb})\,[\alpha - (1/\gamma_s^2)]\,\beta_s^2\,mc^2\,\gamma_s\,(\Delta p/p)_{max}^2 ,$$

where T_0 is the rotation period time of a proton, T_{bb} is the barrier pulse width, and α is the momentum compaction factor and equal to $1/\gamma_t^2$. V_{bb} is given in unit of MV, while mc^2 is a proton mass energy and it is given in MeV. The estimated minimum voltages V_{bb} for the first and second stages are 12.6 and 2.8 keV at the injection time and at the flat top of 31 TeV. We expect a couple times higher voltage V_{bb} than these minimum values will be used. As is shown in the Table I, the acceleration voltage per turn is 1939 kV for the second stage, and the energy loss of a proton per turn at the flat top of 31 TeV is 940 keV, we need accurate voltage control of the acceleration and barrier bucket voltages. As the synchrotron radiation loss is so large, we should expect some Touschet's effect and some effect due to statistical fluctuation of synchrotron radiation in the second stage.

6. Superbunch Beam Production and Luminosity

Because the synchrotron radiation in the first stage is negligible, all of the 114 superbunch beams with the beam length of 300 meters are utilized to maximize the luminosity. Thus we can operate the collider at the maximum luminosity of 1.5×10^{35} $/cm^2/sec$.

In the second stage due to the excessive synchrotron radiation, we limit the number of the superbunch beam to 26, with beam length of 150 meters. There is only one set of core in a induction cell, thus making 0.45 μsec long acceleration pulse. The maximum luminosity in the second stage is 5×10^{34} $/cm^2/sec$.

7. Beam physics Issues and Luminosities

In the Superbunch scheme the continuous parasitic collision is a big issue. Certainly the tune shift for particles within 1σ is remarkably suppressed by utilizing the hybrid crossing, as explained in a previous paper [5]. To suppress the amplitudes of large amplitude particles, the crossing angle should be increased to 400 μ rad. at the expense of 50% loss in the luminosity. Even with this, a 14-TeV center of mass Superbunch hadron collider can deliver the luminosity of $1.5 \times 10^{35}/cm^2/sec$. Since the 62-TeV center of mass Superbunch hadron collider has the same situation, we could expect the luminosity over $1 \times 10^{35}/cm^2/sec$. But due to the big synchrotron radiation loss we should like to limit the luminosity in the order of $5 \times 10^{34}/cm^2/sec$.

In the Superbunch scheme the bunch length is extremely long, about 150 to 300 m, compared with that in the RF bunch scheme. However the bunch is not continuous because it is confined in a barrier bucket with a small synchrotron oscillation frequency. The growth time in the longitudinal direction due to intrabeam scattering is negligible, while that in the transverse direction it is of similar order to the growth time in the RF bunch scheme.

8. Effects of Synchrotron Radiation and Beam Screen

In the first stage, the synchrotron radiation loss is 0.18 W/m/beam with full beam intensity as designed. As the synchrotron radiation hit the vacuum tube at room temperature, there is no serious cooling problem, except some vacuum problem.

In the second stage, we have to install a beam screen inside the vacuum tube, because of huge synchrotron radiation of the beam. The beam screen has a very complicated and delicate mechanical structure that also makes the vacuum problem a complex subject to be studied carefully. These problems are extensively studied and reported in the VLHC report [14].

The energy loss per meter of the synchrotron radiation scales as E^2 x B^2 x I, where I is the beam current. For the 62-TeV center of mass p-p hadron collider the estimated energy loss due to the synchrotron radiation would be 89 W/m/beam, if we had used all of the beam intensity from the first stage. This power would be too much to be handled cryogenically. Therefore we should like to limit the average current, by reducing the number of superbunches. By selecting the number of superbunches 26, and reducing the superbunch length to 150 meters, the synchrotron radiation can be cut to 12 W/m/beam, and the luminosity can be 5 $x10^{34}$ $/cm^2/sec$. We think this much power can be handled cryogenically.

The beam screen is also heated up by the resistive heating due to its image current. The resistive heating of 31 TeV ring is estimated at 0.34 W/m/bore with the average current of 1.1 Amp. At present the LHC group is working hard to develop an efficient beam screen. Thus, the technique developed at LHC will be applied to the 62-TeV collider beneficially.

9. Preliminary Cost Estimation for First stage Collider

The preliminary cost of the 14-TeV first stage collider is estimated to be about 1.9 Billion dollars and is shown in Table II. This is based on the cost estimation done on the 40-TeV first stage of the175-TeV VLHC [14]. The ratio of the circumferences of these two rings is 87.25/233 = 0.37, we took 40 % of the cost of the corresponding components except the items of the Below Ground Construction and the Interaction Regions. We used 50 % for the Below Ground Construction, because we want to build the tunnel with a 3 meter diameter from the beginning to allow for the 62-TeV collider to be installed at a later stage. The cost differential due to the large diameter is rather small when excavating long tunnels. Also we used a higher cost, because we want to install a transit system inside the tunnel.

We estimate the cost of two 62-TeV detectors will be 3 billion dollars, each costing 1.5 Billion dollars. Up to this stage the cost of detectors will be more expensive.

10. Schedule

A possible timetable for the construction of the 14-TeV and 62-TeV collider is shown in Table II, together with the 14-TeV and 62-TeV collider experiment runs. The construction of the first stage of 14-TeV collider can be built with the existing technology, and can be started any time.

The 62-TeV hadron collider can be built with the existing superconducting magnet technology. The only components to be developed for this collider are the 10-Tesla high field superconducting long magnets. Considering the facility and experiences at Fermilab along with the recent trend in the superconductor industry, we should be able to produce prototype magnets for industrial production in six years. From the experiences at CERN, DESY, and others, it is evident that the industry can build all the magnets in the following six years.

11. Conclusions

As a scenario, we should start building the 14-TeV center of mass p-p collider using the 7-TeV first stage ring as soon as possible, because this collider can be built with existing technology. With the superbunch beam scheme in the first stage, we can achieve the luminosity of 1.5 $x10^{35}$ /cm^2/sec, and we should be able to do excellent and still pioneering physics at the 14-TeV center of mass energy with much higher luminosity than LHC.

At the same time we should start designing and building the collider detectors, which will be used first as the 14-TeV center of mass collider detector, but with the intention to expand them into 62-TeV center of mass collider detectors. After several years of experiments at 14-TeV center of mass energy and whenever the high field magnets are ready to be installed, we should switch to the 62-TeV center of mass with a luminosity, like 5 $x10^{34}$/cm^2/sec. The only components to be developed for this collider are the long 10-T high field superconducting magnets with a good beam screen.

12. Appendix : 90 TeV center of mass Hadron Collider with Superbunch Beams

As a simple extension of the 62-TeV center of mass hadron collider, we consider the case with the 90-TeV center of mass hadron collider. Its parameter list is given in Table IV. Its design principle is same as the 62-TeV hadron collider, except the tunnel circumference is enlarged from 87 km to 122 km. The center of mass energy of the first stage will be 20 TeV, by utilizing 2 Tesla low field ring. Its luminosity will be 1.5 x 10^{35} /cm^2/sec.

The center of mass energy of the second stage will be 90 TeV with the 10 Tesla high field magnet ring. If we excite the high field magnet ring to 11.1 Tesla, we will get 100 TeV center of mass energy. The luminosity in the second stage will be 5 x 10^{34} /cm^2/sec. In this scheme we have to use the Tevatron as the injector.

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[14] "Design Study for a Staged Very Large Hadron Collider," ibid, 6.2.2.4 Conceptual Beam-Screen Design, and 10.2.5 Synchrotron Radiation and Vacuum.

[15] "Design Study for a Staged Very Large Hadron Collider," ibid, 9.4 Results and Analysis, Table 9.2.

Table I. Parameter List of 14-TeV and 62-TeV cm Colliders.

	Unit	14-TeV cm	62-TeV cm
Energy of Ring	TeV	7	31
Dipole Field	Tesla	2	10
Injection Energy	TeV	0.15	7
Injection Field	Tesla	0.0429	2.258
Luminosity	cm^2/s	1.5×10^{35}	5×10^{34}
Ring Circumference	km	87.249	87.249
Arc Circumference	km	73.304	64.926
Dipole Filling Factor	%	90	80
Dpl Mag. Field Radius	km	11.667	10.333
No. of P / Bunch		1.3×10^{14}	7.8×10^{13}
No. Bunch / Beam		114	26
No. of P / Beam		1.5×10^{16}	2×10^{15}
Ave. Beam Current	A	8.16	1.1
Synchro. Rad. Loss/B	W/m	0.18	12
Unit Ind. Cell Lngth	m	0.2	0.1
Unit Ind. Cell Volt	kV	2.5	2.5
Rotation Period	μsec	290.83	290.83
Acceleration Energy	TeV	6.85	24
Acceleration Period	Sec	1620	3620
Accele. Voltage /turn	kV/t	1090.6	1938.8
Syn.Rad. Loss /cycle/p	keV	1.9	940
Min.Total V. for BB-IC	kV	12.6	2.8
Ttl No. of Ind. Cells	#	436	1152
Ttl Length for all ICs	m	87.2	115
Coreloss of Unit Cell	kW	2.0 x2	0.45
Total Coreloss	kW	1,706	518
Superbunch Spacing	m	765	3356
Superbunch Length	m	300	150
Time Period /SB	μsec	2.55	11.19
Rep. Rate of IC Pulser	kHz	392	89.4

Table II. Cost Estimation of 14-TeV cm Hadron Collider
Referring to Cost of Stage-1 of VLHC, 40-TeV cm Collider, in Fermilab TM-2149.

Cost Driver	40-TeV cm Collider in M$	14-TeV cm Collider in M$	Cost Ratio in %
Total Cost	4, 138 M$	1,885 M$	45.6
Below Ground Const.	2,125	1063	50
Above Ground Const.	310	124	40
Main Arc Magnets	792	317	40
Correc. & Spec. Mag.	112	45	40
Refrigerator	95	38	40
Other Cryo. Systems	22	9	41
Installation	232	93	40
Vacuum System	154	62	40
Interaction Regions	26	26	100
Other Accelerator Sys.	270	108	40

*14-TeV/40 TeV = 0.35

Table III. Possible Construction Schedule of the 14- and 62-TeV cm Collider

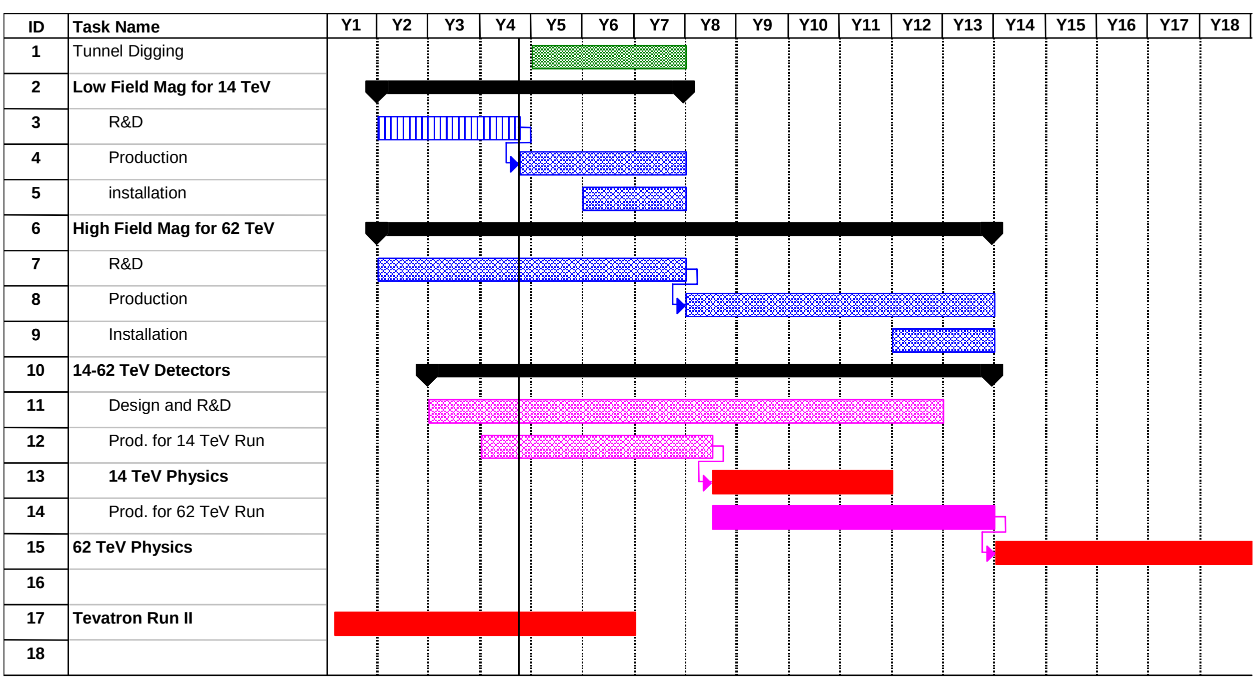

Table IV. Parameter List of 20-TeV and 90-TeV cm Colliders.

	Unit	20-TeV cm	90-TeV cm	100-TeV cm
Energy of Ring	TeV	10	45	50
Dipole Field	Tesla	2	10	11.1
Injection Energy	TeV	0.9	10	10
Injection Field	Tesla	0.18	2.222	2.222
Luminosity	$/cm^2/s$	1.5×10^{35}	5×10^{34}	5×10^{34}
Crossing Angle	μ rad.	400	400	400
Ring Circumference	km	122.155	122.155	122.155
Arc Circumference	km	104.720	94.248	
Dipole Filling Factor	%	90	81	
Dpl Mag. Field Radius	km	16.667	15	
No. of P / Bunch		1.3×10^{14}	7.8×10^{13}	
No. Bunch / Beam		160	26	
No. of P / Beam		2.1×10^{16}	2×10^{15}	
Ave. Beam Current	A	8.18	0.8	
Synchro. Rad. Loss/B	W/m	0.39	19	
Unit Ind. Cell Lngth	m	0.2	0.1	
Unit Ind. Cell Volt	kV	2.5	2.5	
Rotation Period	μsec	407.18	407.18	
Acceleration Energy	TeV	9.1	35	
Acceleration Period	sec	3600	3600	
Accele. Voltage /turn	kV/t	1029	3959	
Syn.Rad. Loss /cycle/p	keV	5.49	2771	
Total V. for BB-IC	kV	93	93	
Ttl No. of Ac IC/B	#	412	2692	
Ttl Length of Ac IC/B	m	82.5	269	
Coreloss of Unit Cell	kW	2.0 x2	0.45	
Total Coreloss/beam	kW	1650	1211	
Superbunch Spacing	m	764	4698	
Superbunch Length	m	300	150	
Time Period /SB	μsec	2.22	15.7	
Rep. Rate of IC Pulser	kHz	393	63.9	

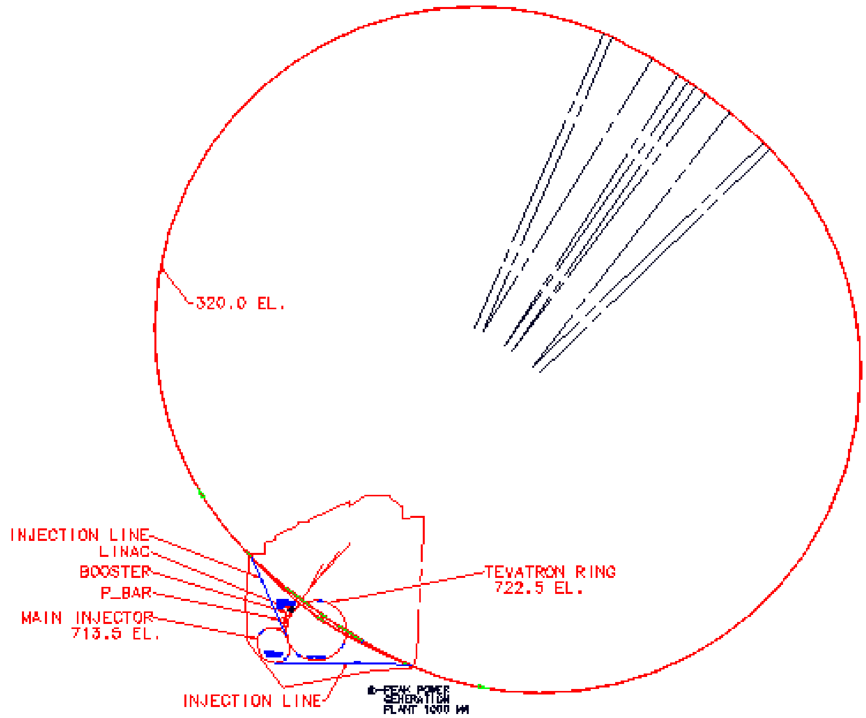

Fig. 1 Overall Layout of 62-TeV P-P Hadron Collider

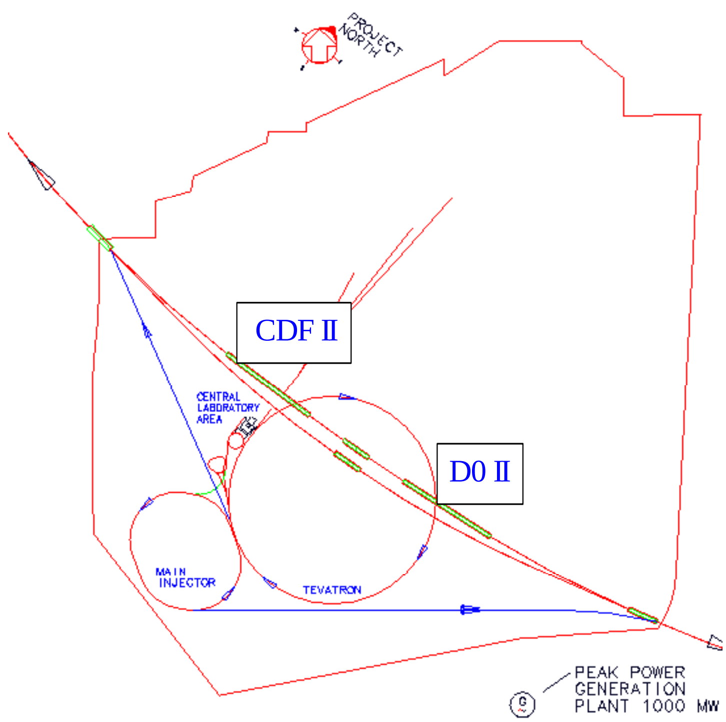

Fig.2 Expanded View of the Fermilab Site. Two major detector interaction regions and four short utility regions are shown. The outward bypass for the low field magnet ring is shown.

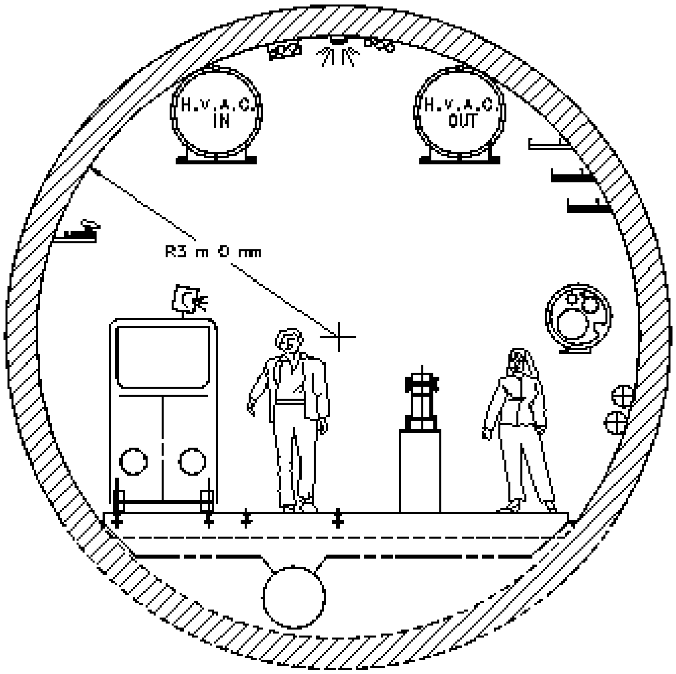

Fig.3. The tunnel cross section is shown with the low field magnet ring of the first stage. The magnet is installed at the optimum height for maintenance. The diameter of the tunnel is set at 6 meters.
The fast transit system is installed for the accelerator maintenance and for personnel transportation. The center lines of the detectors are made to coincide with the center line of the low field magnet ring.

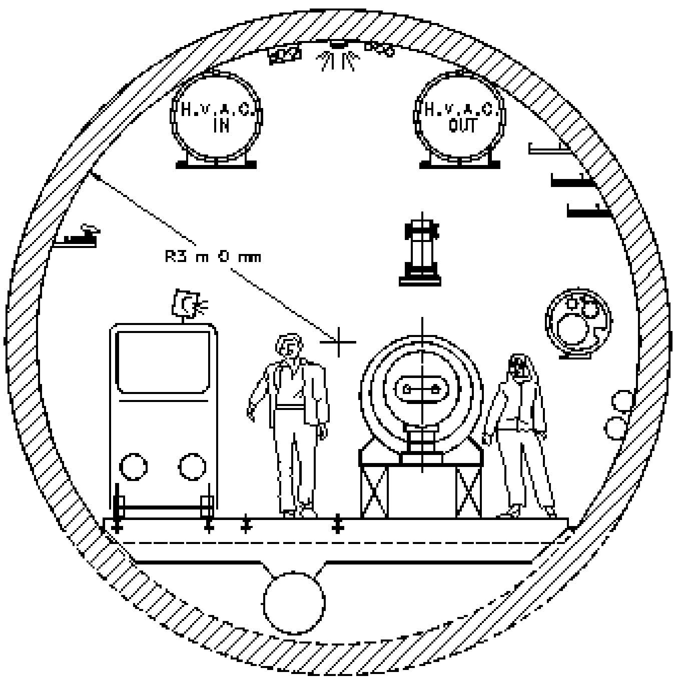

Fig.4. The cross section of the tunnel is shown with both the low and high field magnets installed. The low field magnet is lifted up to make room for the installation of much heavier high field magnets. The detectors are kept at the same height for the 62 TeV runs. Enough space for the maintenance of the high field magnets is reserved on both sides.