25-TeV Center of Mass Hadron Collider
in VLHC Booster Tunnel

Ryuji Yamada, Fermilab
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Abstract:

The concept of building a 25-TeV center of mass collider at Fermilab that uses the VLHC Booster tunnel is investigated and reported in this paper. It could be a P-P collider with high luminosity of 1.0 x 10^{34} /cm^2/s, or a $\bar{P}-P$ collider with a reasonably high luminosity of 2.3 x 10^{33} /cm^2/s. We consider installing it in the proposed tunnel for the 3-TeV VLHC Low Field Booster Ring. The operational magnetic field of the superconducting dipole magnets for the 12.5-TeV ring will be 11.2 Tesla, which is technically feasible with the present technology. The superconducting magnets will be built with Nb$_3$Sn conductor. For the P-P collider, they will be twin-aperture magnets with a similar structure to the LHC superconducting magnets. As a $\bar{P}-P$ collider they will be single-aperture magnets like the SSC magnets. The estimated power of synchrotron radiation to the beam screen is manageable and just a factor 2 bigger than that of LHC. But the total heating of the beam screens is estimated to be about 0.4 W/m/beam both for the 25-TeV P-P collider and the LHC collider. The attainable luminosities and the effects of the synchrotron radiation are estimated for both 25-TeV collider cases. The advantages and disadvantages of both cases are considered and compared.

The 25-TeV collider could be constructed with existing techniques in 10 years, with the cost of one fourth of the 100-TeV high field collider. As a scenario it is suggested to start also the designs of the collider detectors, which start as 6-TeV collider detectors and will be expanded into the 25-TeV collider detectors, thus keeping the high energy physics experiments going in USA.

1. Introduction

As a future project in high energy physics, VLHC is proposed for the future hadron collider [1,2,3,4,5,6]. One of the present plan is to build a 3-TeV Booster and a 100-TeV P-P collider. As a 3-TeV injector, it is proposed to build a booster ring tunnel, which is larger than the present Fermilab site, and the usage of 2 Tesla low field magnets are considered [7,8,9].

If we look back over the histories of many accelerators and colliders, the tunnels built for the original machines are used again and again for the next generation machines. It is true with the Fermilab Main Ring tunnel, which was used for the Tevatron, and same with the CERN PS tunnel, which was used for LEP and LHC [10]. We should consider the possibility of using the VLHC Booster tunnel for a higher energy collider.

In the near future when the 7 x 7 TeV LHC begins its operation, CERN will definitely start serious considerations for their upgrade projects. One of them will be replacing the

8.4 Tesla magnets presently being constructed with higher field magnets. Using 11.2-T dipole magnets, the LHC could reach 18.6 TeV center of mass energy.

If the next 100-TeV or higher collider machine should be built collaboratively with world-wide effort, and if we want some footing in the USA, we should start some project soon which will be able to be used as an injector to compete with the existing European project.

2. Tunnel

The tunnel, which is presently designed for the 3-TeV Low Field Booster Ring, will be built at a depth of 130 meters from the surface, and is expected to only minimally affect the environment on the surface [11]. The parameters of the 3-TeV Booster and its tunnel are shown in Table I. Its total circumference is 34 km and its arc length is 30 km. The layout of the proposed booster tunnel is shown in Figure 1. The magnetic curvature for the 3-TeV ring magnet is 4536 meters, assuming a 95% dipole magnet filling factor. For the 12.5-TeV ring it will be 3820 meters, assuming an 80% dipole magnet filling factor. It has two long straight sections, each roughly two kilometers long: one inside the Fermilab campus and the other one outside the Fermilab site. These two long straight sections will be used for the high energy experiments.

The cross section of the proposed tunnel for the 25-TeV collider is shown in Figure 2. The high field superconducting magnet for the 25-TeV collider is shown together with the magnet of the 3-TeV Booster ring. A cryogenic pipeline for transporting liquid helium is also shown. For maintenance of these components and control cables, the radius of the tunnel is chosen to be 7.5 feet. In the straight sections, the 3-TeV Booster Ring will be bypassed over the high energy experimental detectors, when the high field magnets are installed.

3. High Field Magnet

Presently the high field magnets for high energy physics application are extensively being developed at several institutions in the world, including at Fermilab [12]. The superconducting material, which is being utilized for this high field region is Nb_3Sn. The highest field yet achieved in a magnet of this type is 13.5 Tesla at LBNL [13]. Another magnet developed at University of Twente with Nb_3Sn, obtained 11 Tesla [14]. It seems very reasonable to assume we could produce the 11-T magnets for our application, and possibly 12-T magnets [15,16]. The present Nb_3Sn conductor for high field application has a quite large effective filament diameter, in the order of 20 to 70 microns. It has quite a large magnetization, and causes a big persistent current, generating a substantial sextupole term at injection field. We need an extensive study on the side of superconductor manufacturers. With the industry's rapid trend, we should be able to get good superconductor in a few years.

3.1. High Field Magnet for P-P Collider

We have to design and build twin-aperture magnets, with a similar structure to the LHC magnets or a more innovative structure. An example of twin-aperture magnet

design is shown in Figure 3. After the development of one-aperture magnet as explained for the $\overline{P}-P$ collider, the twin-aperture magnet can be developed.

3.2. High Field Magnet for $\overline{P}-P$ Collider

For a $\overline{P}-P$ collider, we can use the one-aperture magnets with cosine-θ conductor cross section. A typical cross section of the 11-12 Tesla superconducting magnet with 45 mm aperture is shown in Figure 4. Its calculated excitation curve is shown in Figure 5 with and without the iron saturation correction holes in yoke. The short sample data of the presently planned conductor cable and their degraded values are also shown. The details are found in another reports [15,16]. This kind of high field magnet for the collider application could be developed and be ready for mass production in several years.

3.3. Problems Related to High Field Magnet Development

There are several technical problems to be solved for the development of high field superconducting magnet. Some of them are described in details in the other reports [15,16].

First the useable aperture of the magnet should be determined. This requires the detailed and extensive study of dynamic aperture from the accelerator requirement using detailed field quality of the magnets.

Secondly, the field distribution at the injection time is largely determined by the persistent current in the superconductor cable. Presently the effective filament diameter size d_{eff} of the Nb_3Sn superconductor is about 70 microns. Then the sextupole field component is intolerably high at the injection field from 0.9 to 2.7 Tesla, which correspond to 1- and 3-TeV injection energies, respectively, as shown in Figure 6. Some recently developed conductor has a d_{eff} value about 20 microns. We hope this value may be reduced to a few microns in a few years.

Thirdly, we need superconductor with a high current density above 2200 A/mm^2 at 12 Tesla and 4.2 K. This value seems practically available from industry in a few years.

Fourth, the field distortion at the high field due to the saturation of the iron yoke can be controlled with the addition of holes in the iron yoke, as shown in Figure 4 [17].

Fifth, the problems of synchrotron radiation, the beam screen, and the vacuum are described later.

4. Beam Separator

For the $\overline{P}-P$ Collider case we have to install the beam separator in the High Field Magnet Ring to let the proton beam and the antiproton beam circulate simultaneously spiraling in the opposite direction in the same beam aperture as is done with Tevatron. In the Tevatron there are 22 units of electrostatic beam separator modules distributed around the ring to separate colliding beams 5 to 6 mm apart. On both upstream and downstream sides of the CDF and D0 detectors, 3 modules of electrostatic separators are installed. Each module is 100" long and has the electrical potential difference of $\pm$106 kV across 5 cm.

For simplicity, we will design a beam separator system to keep the beams separated by 5 mm for 25-TeV collider. The length of the separator will be 12.5 times longer over the existing beam separator system for the Tevatron. Therefore we would need a long straight section of roughly 125 meters on both sides of the detector. This much of length is already available in the layout of the booster tunnel as shown in Figure 1. We have to study the arrangement of insertion quadrupole magnets and also the arrangement of regular quadrupole magnets in that area.

5. Schemes of Acceleration

There are several schemes of acceleration for energies up to 12.5 TeV. The first choice is whether it is a proton-proton collider or a proton-antiproton collider. The second choice is its injector, whether it uses the proposed 3-TeV Low Field Booster, or uses the existing 1-TeV Tevatron. The major related parameters for each choice are listed in Table I.

5.1. 25-TeV P-P Collider with 3-TeV Low Field Booster

In this scheme, the 150-GeV Main Injector will provide proton beams to both apertures of the 3-TeV Low Field Booster, in succession. These two proton beams are accelerated to 3 TeV simultaneously and injected into the two apertures of the High Field Magnet, and accelerated into 12.5-TeV beams simultaneously. In this scheme, we have to install two transport lines from the main injector to the 3-TeV Booster as shown in Figure 1. This scheme is very straightforward and can achieve the high luminosity of 1.0×10^{34} /cm^2/s without any difficulty.

5.2. 25-TeV P-P Collider with 1-TeV Tevatron as Injector

With this scheme, we can avoid building the 3-TeV Low Field Booster Ring, and use the tunnel for the High Field Magnet Ring alone. The Tevatron accelerates the 150-GeV beams from the Main Injector up to 1 TeV. Two strings of 1-TeV beams will be injected into the twin apertures of the High Field Magnet Ring in succession as the two counter-circulating beams. We will need two 1-TeV injection lines from the Tevatron to the new booster tunnel. With this scheme we should be able to get the high luminosity of 1.0×10^{34} /cm^2/s as in the previous case.

Corresponding to the 0.9 Tesla injection field with a lower injection energy of 1 TeV, the effect of the persistent current is more severe than that of the previous 3-TeV injection.

5.3. 25-TeV $\overline{P} - P$ Collider with 3-TeV Low Field Booster

The antiproton beam is accumulated in the anti-proton beam complex and accelerated by the 150-GeV Main Injector. The successive 150-GeV antiproton beams will be injected into the 3-TeV Low Field Booster Ring and then accelerated to 3 TeV. Successive 3-TeV antiproton beams are injected and stored in the high Field Magnet Ring.

The 3-TeV proton beam can be achieved with high intensity and without any difficulty from the string of the 150-GeV Main Injector and the 3-TeV Low Field Booster. Then the proton beam will be injected into the High Field Ring. The 3-TeV antiproton and proton beams will be accelerated to 12.5 TeV simultaneously.

We have to use the same aperture of the Low Field Booster Ring for the acceleration of both antiproton and proton beams in time sharing mode, because we will not install the beam separation system in the 3-TeV Low Field Booster Ring.

5.4. 25-TeV $\bar{P}-P$ Collider with Tevatron as Injector

The antiproton beam is accumulated in the anti-proton beam complex and accelerated by the 150-GeV Main Injector. The successive 150-GeV antiproton beams will be injected into the Tevatron and then accelerated to 1 TeV. Then the 1-TeV antiproton beam will be injected and stored in the High Field Magnet Ring. After five 1-TeV sausage-shaped beams are injected and stored into the High Field Magnet Ring, the 1-TeV proton beam with high intensity will be injected into the High Field Magnet Ring. Then both beams will be accelerated to 12.5 TeV together.

We will use the Tevatron for the acceleration of both antiproton and proton beams in time sharing mode. We will need two 1-TeV injection lines from the Tevatron to the new 3-TeV Booster tunnel.

6. Luminosity

6.1. Luminosity for P-P Colliders

With P-P Collider option, we can easily obtain the luminosity of 1.0×10^{34} /cm^2/s, as is the case for the 100-TeV hadron collider [4,5,6]. We assume the same cell configuration as that of "3 TeV Collider P P option (Low Field)" [4,5]. The luminosity is proportional to γ x N_p^2, where γ is the ratio of the total energy of the proton over its rest mass energy and N_p is the number of protons. By increasing the proton number per bunch from 1.1 x 10^{11} to 1.4 x 10^{11}, and with the increase of the γ factor by 4.17, we can get the typical luminosity of 1.0 x 10^{34} /cm^2/s, as shown in Table II.

6.2. Luminosity for $\bar{P}-P$ Colliders

To estimate the luminosity of the $\bar{P}-P$ collider operation, we follow the case of "3 TeV Collider Pbar P option (Low Field)" [4,5]. We use the same numbers of protons and antiprotons in our case. The number of protons per bunch is 2.7 x 10^{11}, and that of antiprotons per bunch is 1.3 x 10^{10}. With the increase of the γ factor by 4.17, the typical luminosity will be 2.3 x 10^{33} /cm^2/s, as shown in Table II. The presently available total number of 1.0 x 10^{13} antiprotons limits the number of antiprotons per bunch.

With the further development in the antiproton source in the future, the total number of antiprotons will be definitely increased, and the typical luminosity value can be increased. From the standpoint of synchrotron radiation, the number of protons should be reduced, when the number of the antiprotons is increased, while increasing the luminosity.

7. Effects of Synchrotron Radiation and Beam Screen

Because of synchrotron radiation of the beam, we have to install a beam screen inside the vacuum tube. This complicates the technical problems we will face. The beam screen has a very complicated and delicate mechanical structure that makes the vacuum problem a complex subject to be studied carefully [18]. The arrangements of the beam screen for different sizes of magnet aperture are shown to full-scale in Figure 7. The beam screen is as long as the vacuum tube of dipole magnets and is over 10 meter long. Its delicately assembled structure has to be inserted into the vacuum tube.

The beam screen is heated up mainly by two phenomena: the synchrotron radiation of the beam and the resistive heating due to its image current [18]. 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 25-TeV CM P-P collider the estimated energy loss due to the synchrotron radiation is 0.343 W/m/beam with the current of 157 mA, as shown in Table II with other related parameters.   The LHC has a nominal synchrotron radiation energy loss of 0.206 W/m/beam with the average current of 536 mA.

The resistive heating for the LHC is about 0.165 W/m/beam. The beam currents in the 25-TeV colliders are about one-third of the LHC value, resulting in a resistive heating of 0.048 W/m.   Therefore the total heating power to the beam screen is about 0.4 W/m/beam for both the LHC and 25-TeV P-P colliders. 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 25-TeV collider beneficially

For the 25-TeV CM $\bar{P}-P$ collider, the synchrotron radiation loss is estimated 0.691 W/m for both beams combined. Its resistive heating is 0.097 W/m, and the total heating will be 0.788 W/m, which is about twice the LHC value. As mentioned in the section on the luminosity, the ratio of the proton and the antiproton numbers in bunches can be adjusted to reduce the total synchrotron radiation loss while keeping the luminosity the same in the future. Therefore the contribution from the synchrotron radiation can be expected to be made smaller in the future with the improvement of the Pbar source.

For the reference, the synchrotron radiation for a 100-TeV collider is estimated to be 5.87 W/m/beam for the average beam current of 135 mA corresponding to the luminosity of 1.0 x 10^{34} /cm^2/s. That value of synchrotron radiation energy loss per meter is about 30 times the LHC value [6,19].

The estimated electrical power needed to keep the beam screen working at 20 K is calculated and listed also in Table II. It comes out to be 1.1 MW for the 25-TeV P-P and $\bar{P}-P$ colliders, but it goes up to about 60 MW for the 100-TeV collider.

8. Advantages and Disadvantages of P-P Collider

With the P-P collider, the luminosity of 1.0x10^{34} /cm^2/s can be easily achieved. As the magnets are twin-aperture superconducting magnets, we have to use twice as much superconductor cable to build the P-P collider compared to the $\bar{P}-P$ collider. The Nb$_3$Sn superconductor is the most expensive material and thus the P-P collider is more expensive to build than the $\bar{P}-P$ collider. The twin-aperture magnet is also technically harder to build than the single-aperture magnet.

9. Advantages and Disadvantages of $\overline{P}-P$ Collider

The achievable luminosity is not as high as in the P-P collider, but we can still expect a substantial luminosity in the order of 2.3×10^{33} /cm^2/s in this case. With further study it could be increased more.

As we only need a single-aperture magnet for this case, the building cost of the magnet and the cryogenic system will be substantially cheaper than the P-P collider case.

The existing $\overline{P}$ source at Fermilab, including the Recycler magnet system can be used. Modifications of these components to increase the number of antiprotons will be needed.

If the 12.5-TeV High Field Magnet Ring should be used as an injector for the much higher energy P-P collider, this collider ring also will do the job with one aperture.

10. Conclusions

The 25-TeV P-P Collider with the luminosity of 1×10^{34} /cm^2/s can be built with the existing superconducting magnet technology in the 3-TeV Booster tunnel. The only components to be developed for this collider are the 11.2-T high field superconducting 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 five years. From the experiences at CERN, DESY, and others, it is evident that the industry can build all the magnets in the following five years.

The cost of the 25-TeV P-P Collider will be about one-fifth of the 100-TeV P-P High Field Magnet Collider because its circumference is much less and the booster tunnel will be available.

The 25-TeV $\overline{P}-P$ Collider can achieve a luminosity of 2.3×10^{33} /cm^2/s or more with further study and development. Because we will use single-aperture magnets instead of twin-aperture magnets in this case, the cost of the high field superconducting magnets will be reduced substantially. Thus the cost of the 25-TeV $\overline{P}-P$ Collider will be substantially less than that of the 25-TeV P-P Collider.

With the 25-TeV P-P Collider the total heating of the beam screen due to the synchrotron radiation and resistive wall heating is about the same as in the case of the LHC. Its related problems, including the cooling of the beam screen and the vacuum system, will be a little harder problem for us to solve than the case of the LHC, because of our smaller aperture. But as the LHC group is presently working hard on this, it is expected to be practically manageable in our case. With the 25-TeV $\overline{P}-P$ Collider, a similar effect on the beam screeen will be extected.

We want to build the booster tunnel with a 15-foot diameter size from the beginning to allow for the 25-TeV collider to be installed at a later stage. The cost differential due to the large diameter tunnel is rather small when excavating long tunnels.

Either the P-P or $\overline{P}-P$ 12.5-TeV ring should be considered as an injector for the future ultra VLHC, which will definitely be built with a real international collaboration.

As a scenario, we should start building the 3-TeV Booster machine as soon as possible. At the same time we should start designing and building the collider detectors, which will be used first as the 6-TeV CM collider detectors, but with the intention to

expand them into 25-TeV CM collider detectors. After several years of experiments at 6 TeV energy and whenever the high field magnets are ready to be installed, we should switch to the 25-TeV CM collider. In this way, we can keep the high energy physics experiments running and high energy physicists working in the USA.

11. References

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[18] "LHC", ibid. Table I, p. 5, p. 52, p. 122, p. 139, and p. 167.
[19] T.K. Kroc, "Synchrotron Radiation in the VLHC", VLHC Information Packet, ibid. In this case, the estimated synchrotron radiation energy loss is 2 W/m/beam with 1.08×10^{14} protons per beam.

Table I.   Parameter List of 3-TeV Booster and 25-TeV Colliders

	Units	3-TeV Booster	25-TeV P-P With 3-TeV Booster	25-TeV P-P With 1-TeV Tevatron	25-TeV $\bar{P}-P$ With 3-TeV Booster	25-TeV $\bar{P}-P$ With 1-TeV Tevatron
Energy of Ring	TeV	3	12.5	12.5	12.5	12.5
Dipole Field	T	2.15	11.2	11.2	11.2	11.2
Injection Energy	TeV	0.15	3	1	3	1
Injection Field	T	0.1	2.7	0.9	2.7	0.9
Luminosity	/cm^2/s	1.9 x10^{33}	1.0 x10^{34}	1.0 x10^{34}	2.3 x10^{33}	2.3 x10^{33}
Ring Circumference	km	34	34	34	34	34
Arc Circumference	km	30	30	30	30	30
Dipole Filling Factor	%	95	80	80	80	80
Dipole Mag. Field Radius	m	4536	3820	3820	3820	3820
No. of Straight Section	#	2	2		2	
Length of Straight Sec.	km	2.0	2.0		2.0	
No. of Utili. Section	#	4	4		4	
Length of Utility Section	km	0.1	0.1		0.1	
No. of Cells	#	240	240		240	
Length of Cell	m	125	125		125	
Phase Advance / cell	°	60	60		60	
No. of Dipole / cell	#	10	10		10	
Length of a Dipole	m	12.25	10		10	
Reference #		[4,7,8,9]				

Table II. Parameters of 25-TeV Colliders compared with other Colliders

|	Units	Tevatron	SSC	LHC	100-TeV CM P-P VLHC	25-TeV CM P-P	25-TeV CM $\overline{P}-P$	3-TeV Pipetron
					High Field			Low Field
Mode		$\overline{P}-P$	P-P	P-P	P-P	P-P	$\overline{P}-P$	P-P
Max. E	TeV	1	20	7	50	12.5	12.5	3
Bend. Radius R	km		10.187	2.784	13.3	3.82	3.82	4.536
Dipole Field	**T**	**4.4**	**6.55**	**8.386**	**12.5**	**11.2**	**11.2**	**2**
Inj. Field	T		0.66	0.539	0.72	2.7 / 0.9	2.7 / 0.9	0.1
Inj. Energy	TeV		2	0.45	3	3 / 1	3 / 1	0.15
Aperture Dia.	mm	75	50	56	45	45	50	38w, 18h
Circumfer.	km		87.1	26.659	89	34	34	34
No. of P /bunch	#		7.5×10^{9}	1.05×10^{11}	1.25×10^{10}	1.4×10^{11}	2.7×10^{11}	1.1×10^{11}
No. of $\overline{P}$/bunch	#						1.3×10^{10}	
No. of bunch	#		17424	3564	20,000	790	790	790
No. of P/beam	#		1.31×10^{14}	3.56×10^{14}	2.5×10^{14}	1.11×10^{14}	2.13×10^{14}	0.869×10^{14}
No. of $\overline{P}$/beam	#						1.0×10^{13}	
Luminosity	**/cm^2/s**		**1.0×10^{33}**	**1.0×10^{34}**	**1.0×10^{34}**	**1.0×10^{34}**	**2.25×10^{33}**	**1.9×10^{33}**
Beam Current I	**A**		**0.07**	**0.536**	**0.135**	**0.157**	**0.316**	**0.123**
							together	
B^2 x E^2			17,161	3,446	392,188	19,600	19,600	36
								3 TeV
Syn. Rad. / beam								
Total E / beam For ttl Ring	KW		9	3.6	492	8.24	16.6 together	
E loss /m /beam	**W/m**			**0.206**	**5.87**	**0.343**	**0.691 together**	
Resistive Loss /m/beam	W/m			0.165	0.042	0.048	0.097 together	
Total Heating E. /m/beam	**W/m**			**0.371**	**5.91**	**0.391**	**0.788 together**	
Elec. Power for 20k He	MW	W/mx2πR X2, X60		**0.778**	**59.3**	**1.126**	**1.135**	
Reference #				[10, 18]	[6]			[4]

10
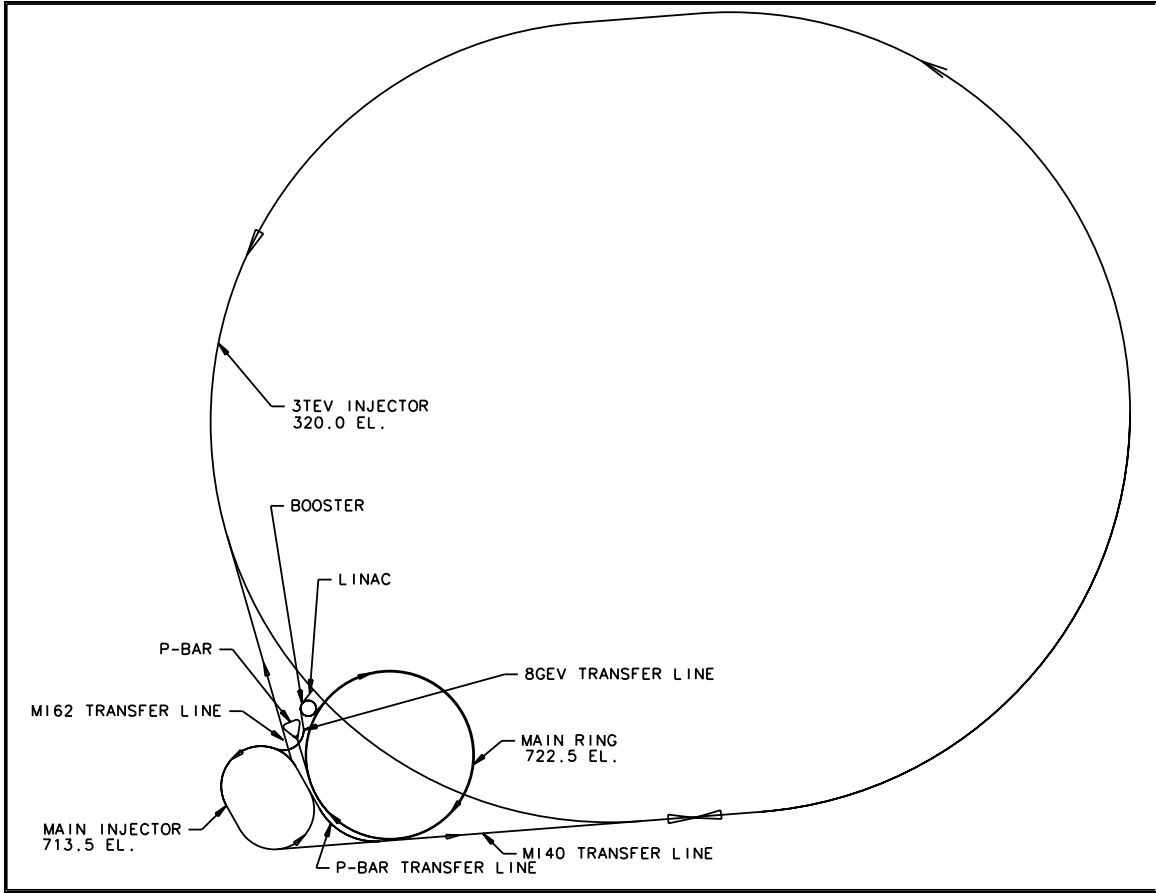
Figure 1. Layout of the booster tunnel for 3-TeV Booster. The same tunnel will be used for the 25-TeV collider and their collider detectors.
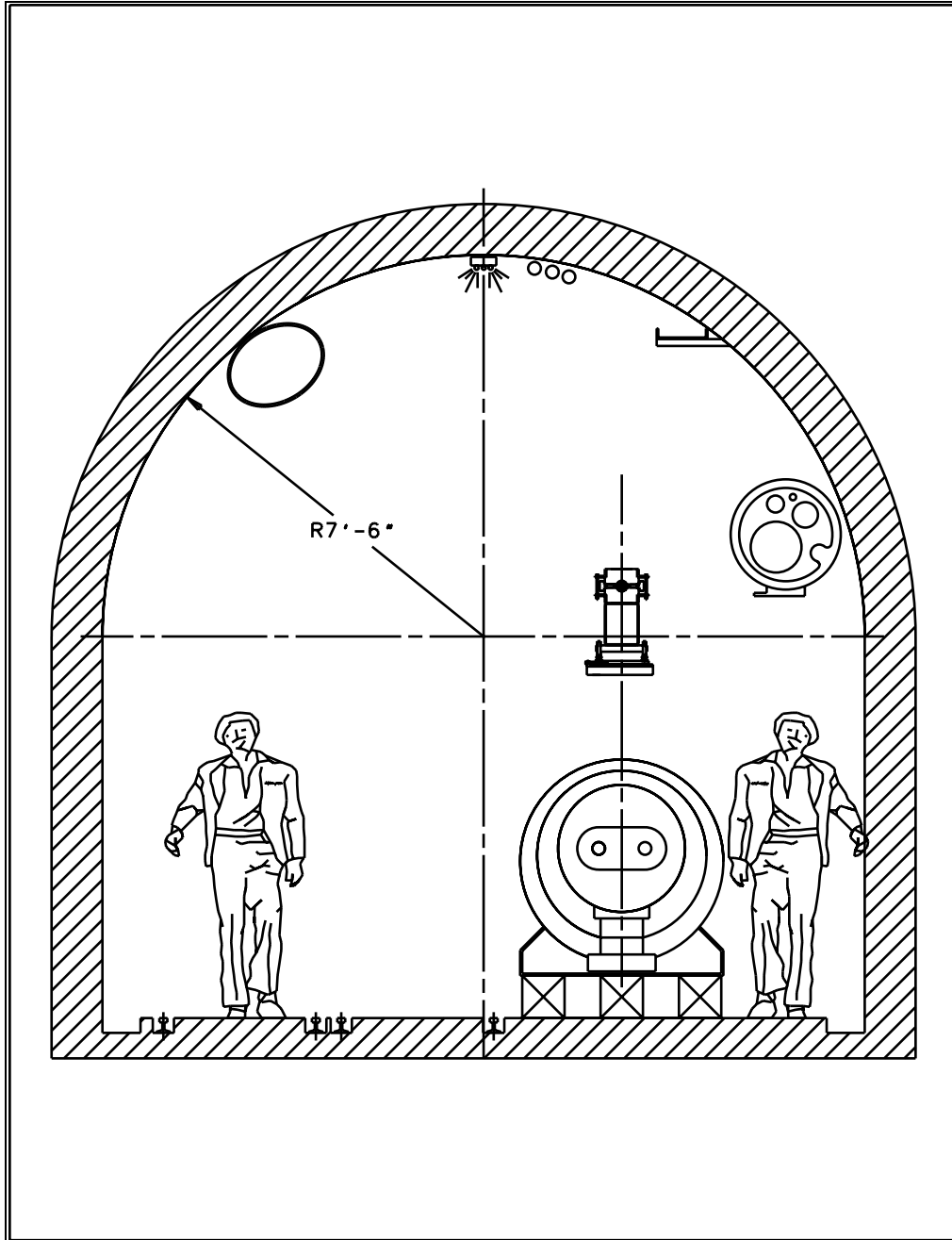
**Figure 2. Cross-section of the 25-TeV collider tunnel. It houses
the 3-TeV Booster ring and the 25-TeV collider magnets.**
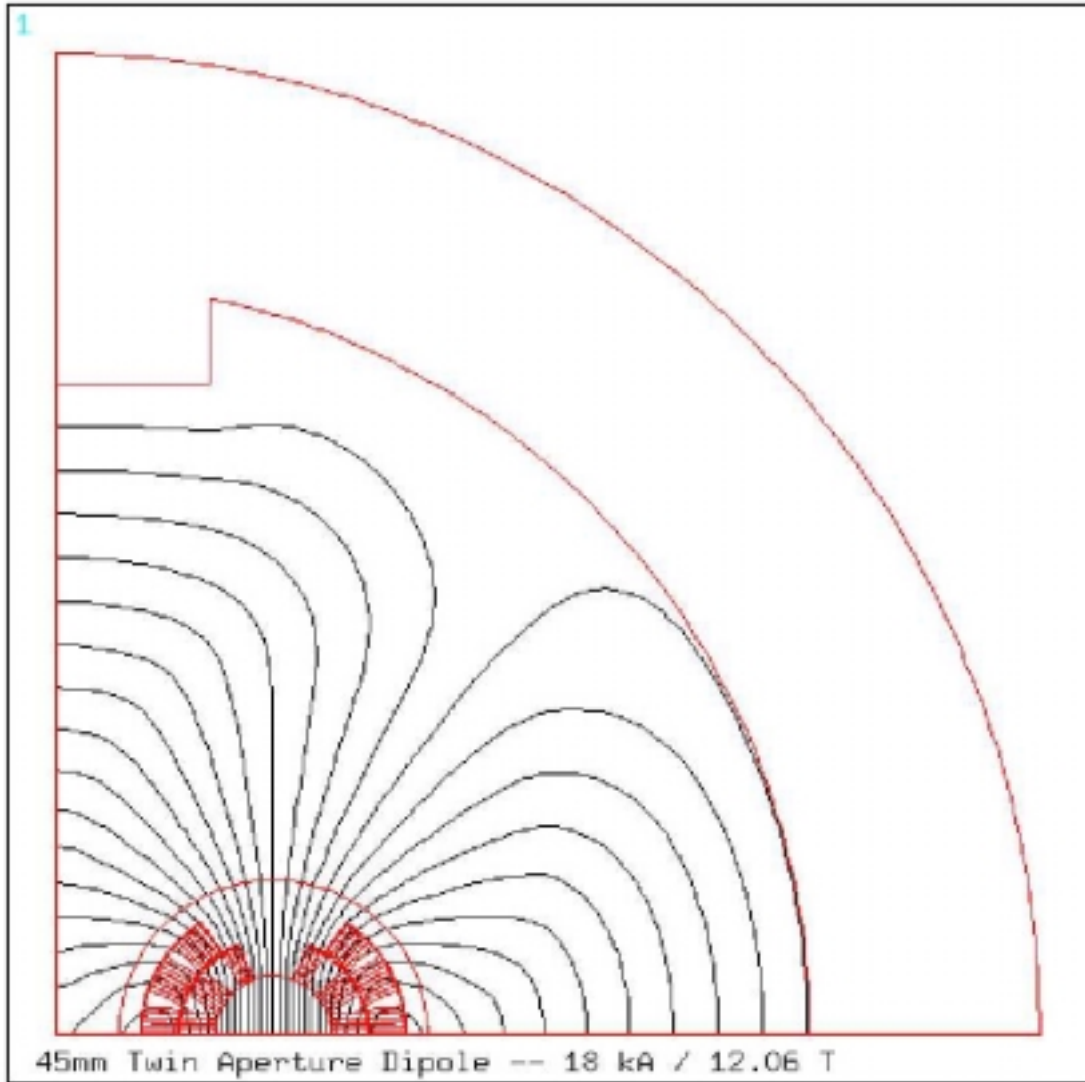
1

45mm Twin Aperture Dipole -- 18 kA / 12.06 T

**Figure 3. Cross-section of a typical twin aperture dipole magnet
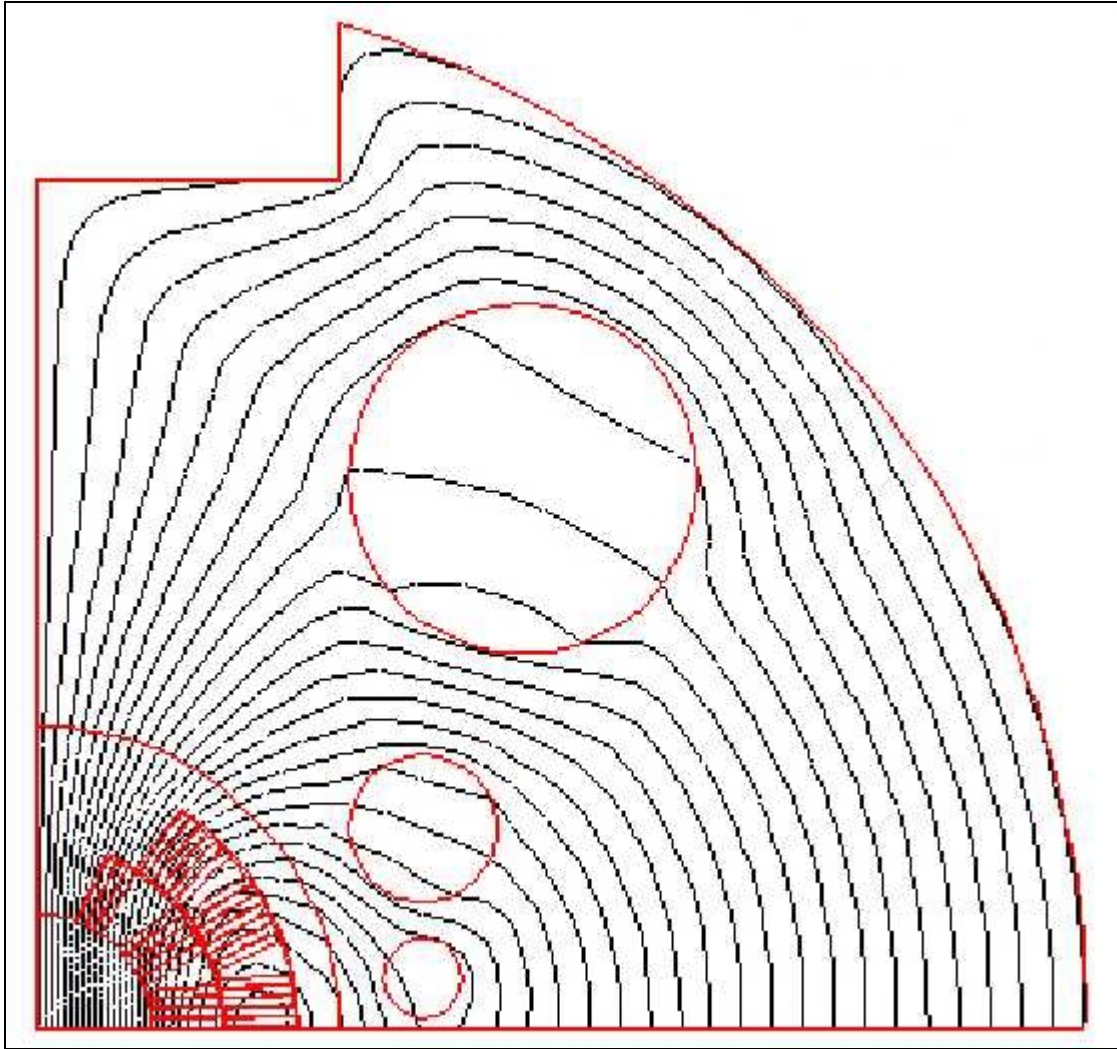shown with the magnetic flux at a 12 T central field.**

Figure 4. Cross-section of a typical single aperture dipole magnet shown with magnetic flux lines at a central field of 12 T. The yoke has several holes for the iron saturation correction.
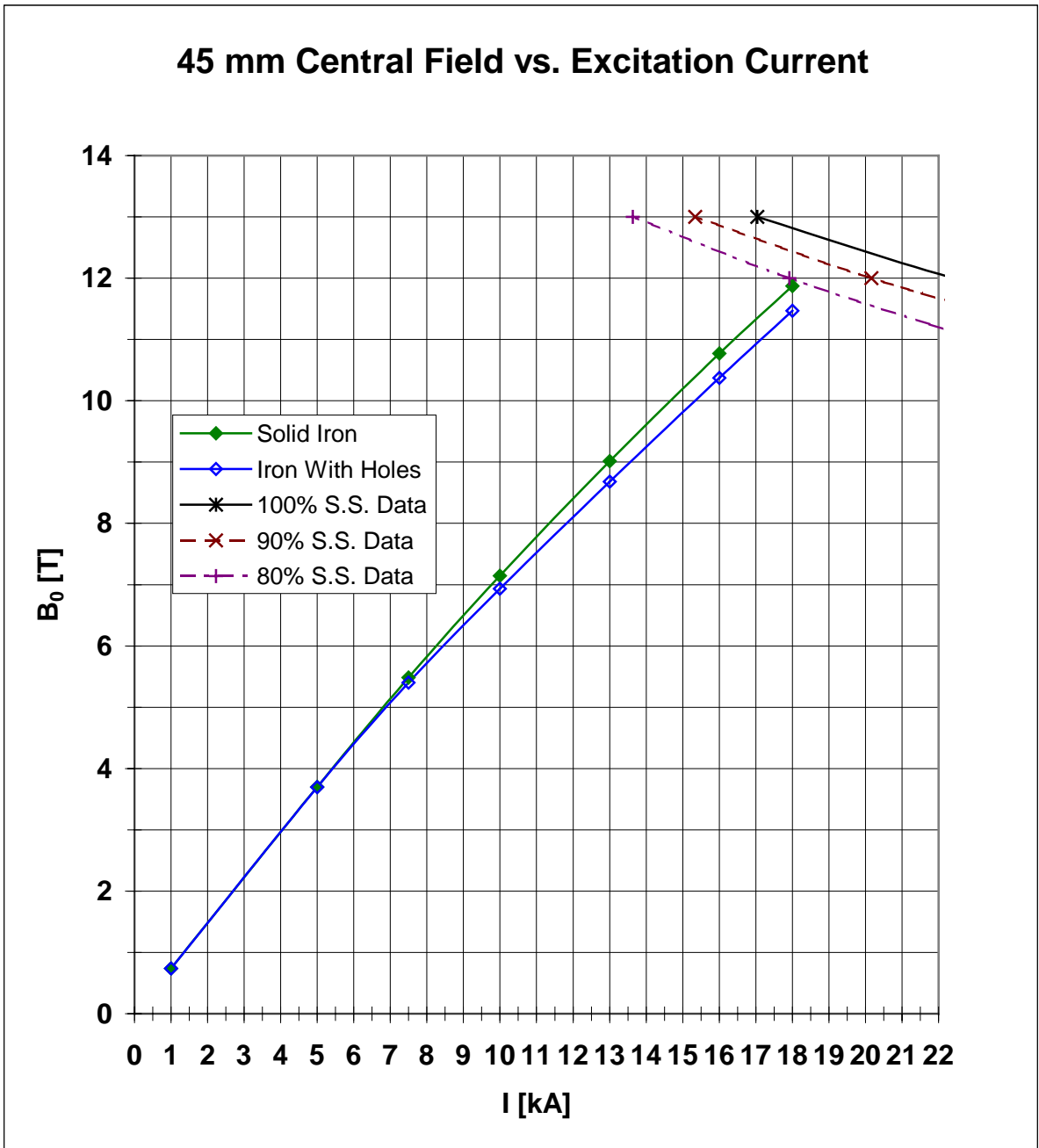
45 mm Central Field vs. Excitation Current

Figure 5. Excitation curves of a typical 45-mm aperture magnet with and without the iron saturation correction holes in yoke. The short sample data of the presently planned conductor are shown together with degraded values.
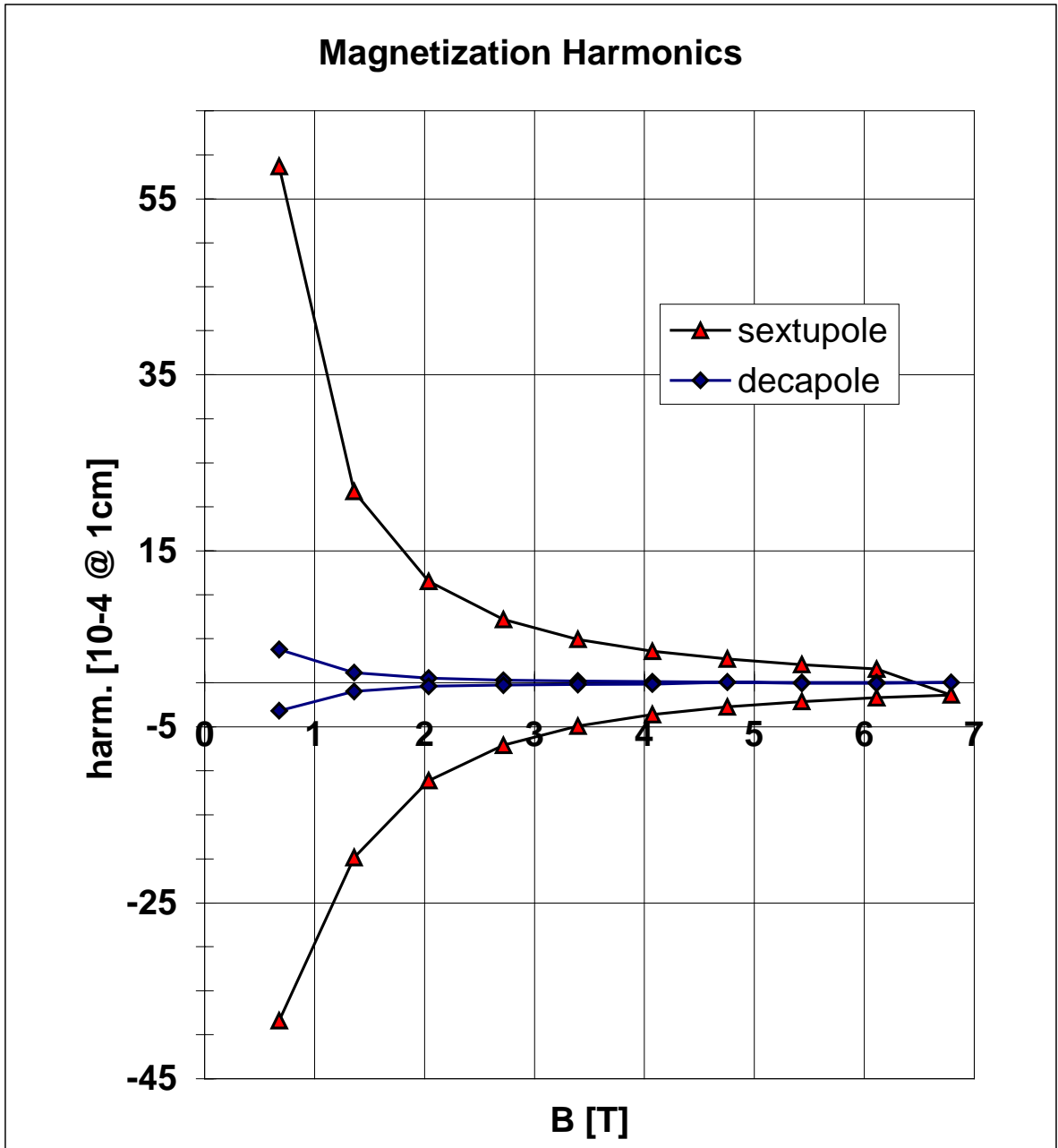
Figure 6. The sextupole and decapole harmonic components are shown for the injection field B. With 1- and 3-TeV injection, the injection field values are 0.9 and 2.7 T. This data is calculated with a filament size of 70 microns. We should expect it will be reduced to below 20 microns.

Beam Screen Arrangement

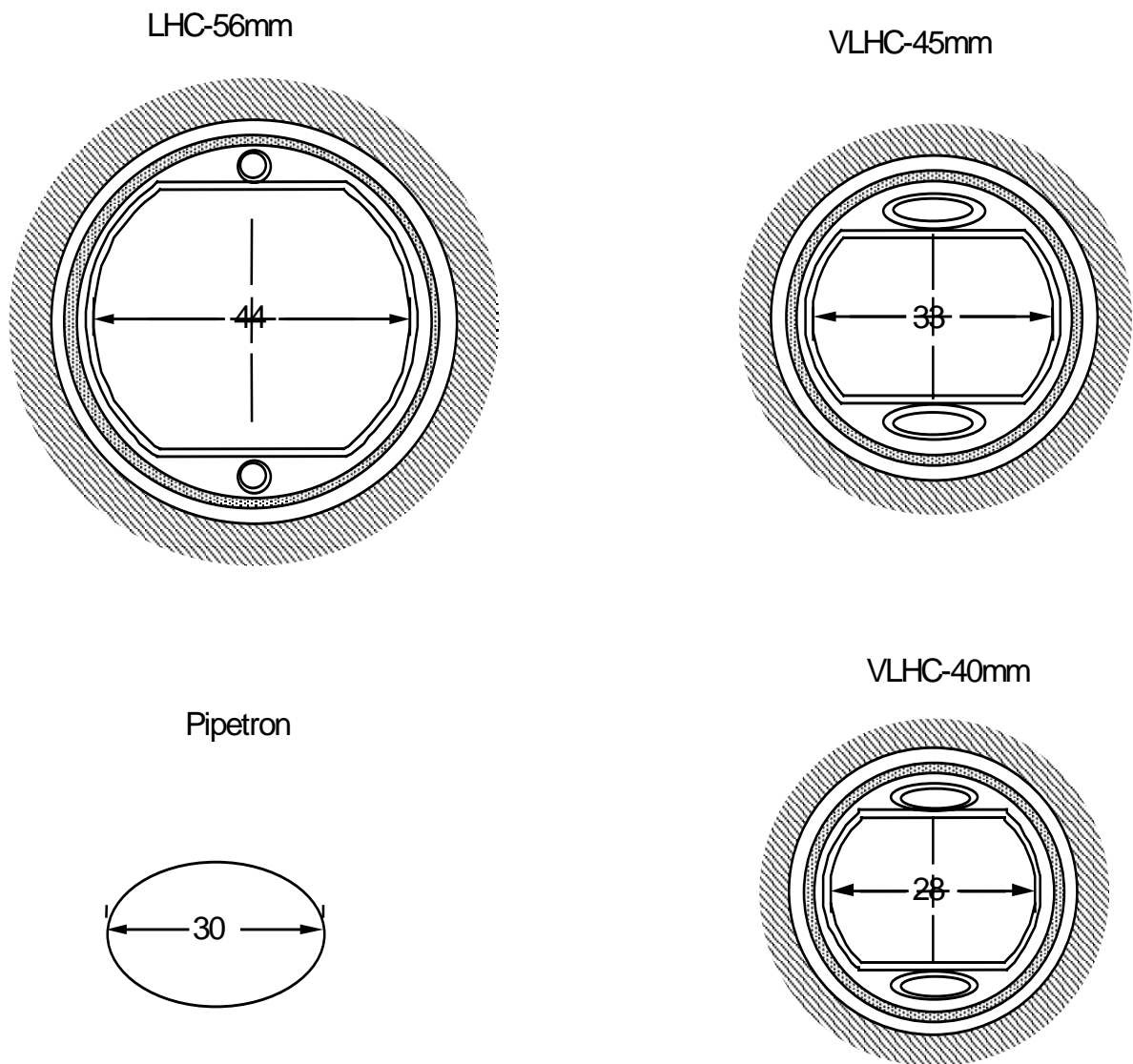LHC-56mm

VLHC-45mm

44

38

VLHC-40mm

Pipetron

30

28

Figure 7. Arrangement of beam screen shown to full-scale in several different configurations. The relative sizes of magnet aperture and beam screen are shown with the available space for beam operation.