Specification of the HADES Superconducting Torus System

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1 Overview

1.1 The HADES Project

HADES is a High Acceptance DiElectron Spectrometer which will be build to investigate hot and dense nuclear matter formed in Heavy Ion collisions at incident beam energies of a few GeV per nucleon. The main goal of the project is to identify electron-positron pairs produced in e.g. central Au + Au collisions on a level of 10^{-6} per collision. This task is particularly difficult since about 200 charged particles are produced simultaneously within the same angular and momentum range. The motivation for these investigations is based on the lack of final state interaction of the leptons which makes them the ideal probe to investigate the interior of the hot and dense volume of nuclear matter formed in such collisions.

The HADES project was approved in July 1994. The collaboration consists currently of about 85 members from 15 Institutions in 8 European countries.

1.2 The HADES Setup

1.2.1 General considerations

The HADES setup will be used to investigate electron-positron pairs emitted in heavy-ion collisions. The momenta of the leptons as well as of other charged particles are determined with an accuracy of about 2%-2.5% (full width half maximum) by particle deflection in a magnetic field. A toroidal field geometry is chosen in order to provide a nearly field free region around the target which is needed to operate a ring-imaging Cerenkov counter. The magnetic field is generated by 6 superconducting coils surrounding the beam (z) axis. It deflects particles like protons, pions and electrons emitted with momenta of several 100 MeV/c by typically 5^{o} to 20^{o}. The spectrometer is a non-focusing device.

The separation of rare electron-positron pairs from pions and protons requires a design which produces only small amounts of secondary electrons. Therefore materials with low atomic numbers (Aluminum instead of stainless steel) should be chosen for the construction. The azimuthal region in between the coils should not contain any solid material. Thus, each coil needs its own vacuum chamber. In order to obtain a large solid angle for the particles emitted from the target and to keep secondary particle production small, coil cases should be very compact. In particular, the width of the coil case should be kept as small as possible.

1.2.2 The HADES Components

The dilepton spectrometer HADES consists of (see Figure 1):

- A ring-imaging Cerenkov detector (RICH) which needs a (nearly) field free region around the target.
- A toroidal magnetic field provided by superconducting coils.
- Tracking detectors inside and surrounding the Torus (MDC's).
- A time-of-flight (TOF) and shower detector array.

The setup is azimuthally segmented into 6 identical sectors surrounding the beam (z) axis (see Figure 2).

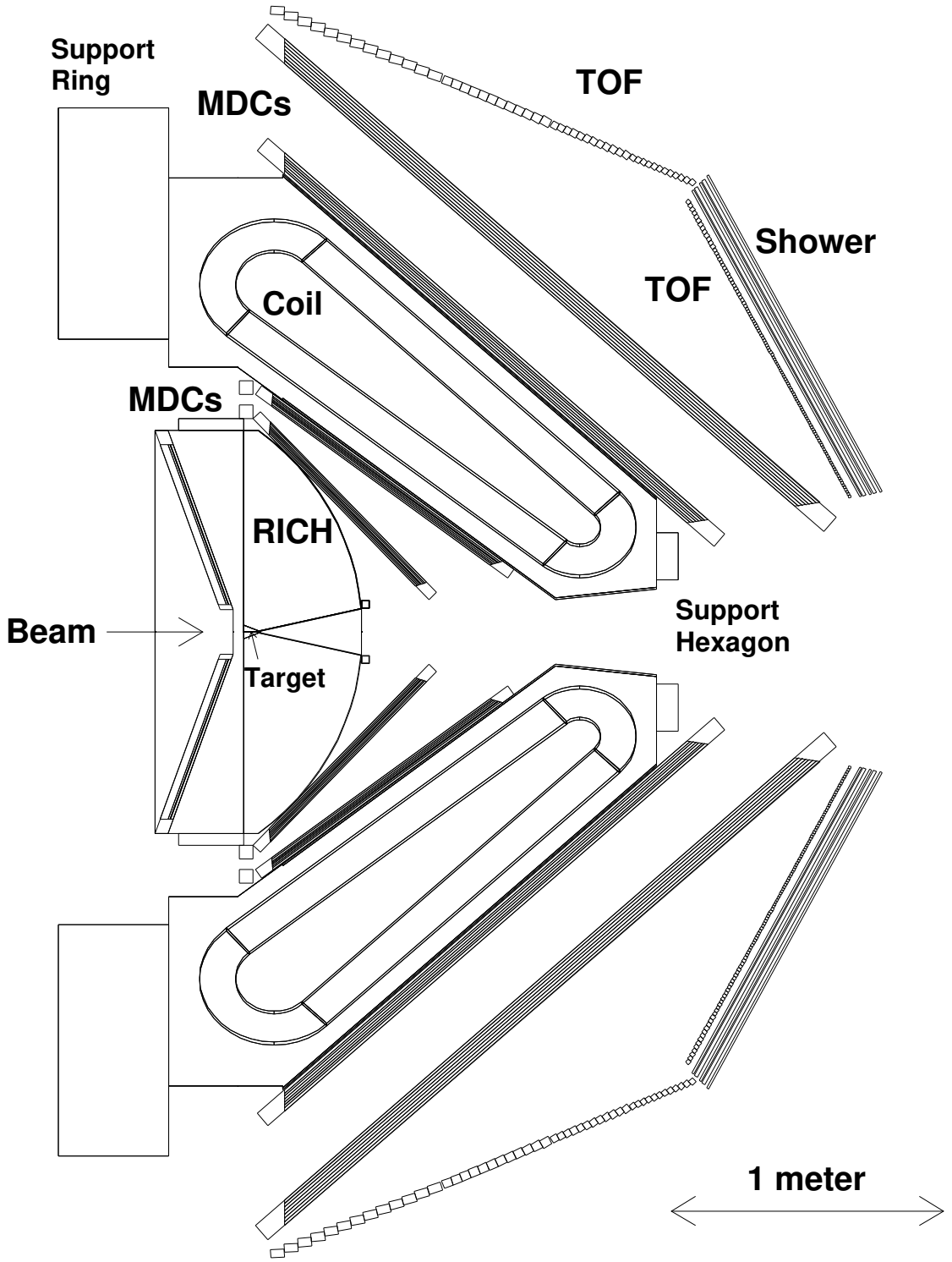

Figure 1: *Cross section through the HADES setup. Coils are projected into the plane shown.*

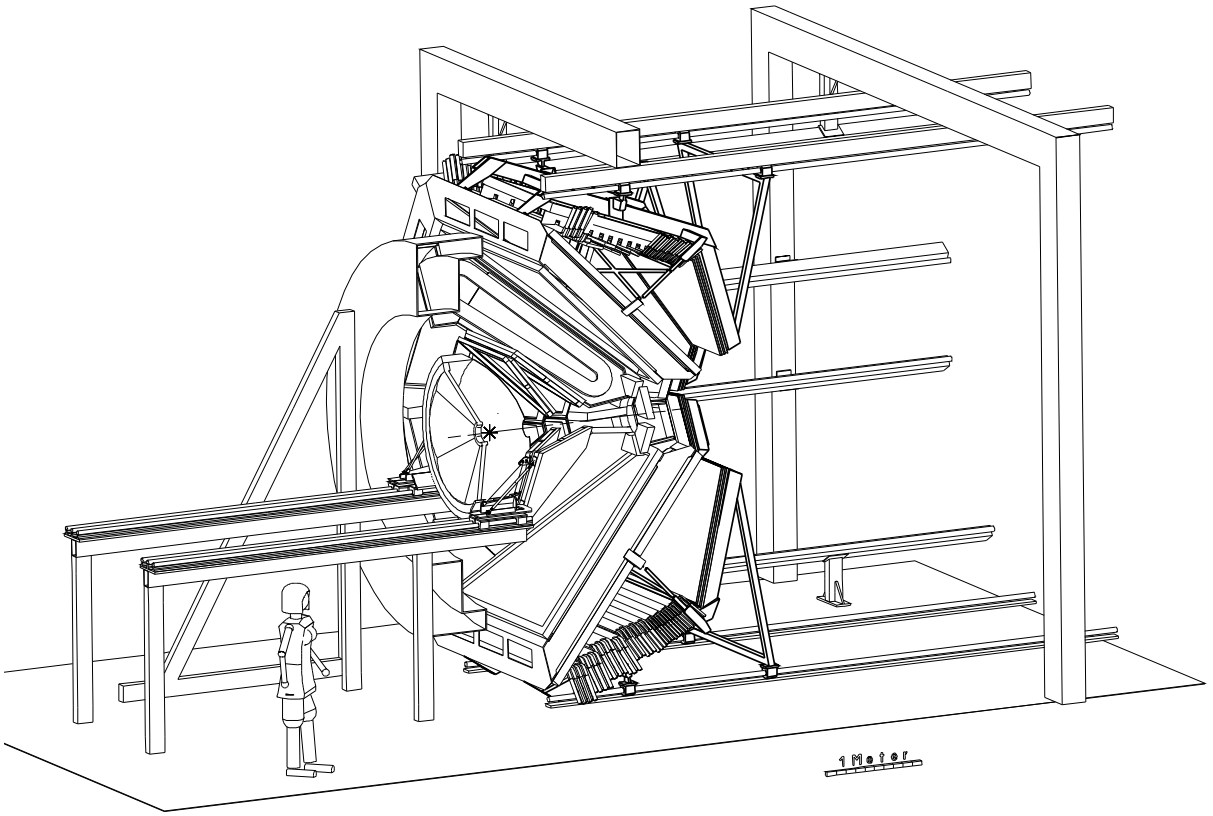

Figure 2: *Three dimensional view of the HADES setup including the support structure of the detectors. The beam enters the setup at a height of 2.5 m.*

2 Specification Overview

The following list gives an overview over the different items and procedures which should be specified in the offer. More detailed information can be found in the following sections.

2.1 Geometry

For several components „Keep In“ zones are defined in sections 3.2 and 3.3, respectively. If not specified otherwise, these „Keep In“ zones represent upper limits including tolerances. Certain regions of the setup are declared as „Keep Out“ zones(see section 3.3). No components of the magnet system should be placed in these regions. For the following items dimensions in the sense of „Keep In“ zones should be guaranteed by the tenderer in his offer with reference to engineering (scale) drawings showing the relevant dimensions:

I. Coil Case, rear support ring and front hexagon of the cryostat (cf. Figure 1, Figure 4).

II. Position and dimensions of the cryogenics interface.

III. Position and size of the flange for the vacuum pump.

IV. Position and size of the power leads.

V. Dimensions of the main support structure for the cryostat.

In addition the geometry of the coils and the coil support should be specified (cf. section 3.1) :

I. Coil cross section, coil shape

II. Cable cross section, number of turns

III. Position and dimensions of a cold support structure stabilizing each coil.

IV. Depending on the method used: Position and dimensions of the cold support structure connecting the 6 coils (if used) or position and dimensions of the coil support connecting the coils individually to the coil case.

2.2 Alignment

The limits on the alignment accuracy and the constraints on the alignment procedure are described in section 7. An alignment accuracy and a verification method should be specified for the following parts:

I. Coils at full and at low (10%) field.

II. Cryostat (warm and cold system, full and low (10%) field)

2.3 Materials

The choice of materials with low atomic numbers (e.g. Aluminum) is of particular importance to keep the production of secondary reaction products as small as possible. However, in the backward region behind the production target the constraints are less severe and the choice of materials like stainless steel can be considered. The following thicknesses and material properties should be guaranteed:

I. Upper limits for the effective thickness of the coils together with the coil cases normalized to the radiation length of the materials used (cf. section 6.1).

II. Average effective thickness of the forward support hexagon for regions A and B, respectively (cf. section 6):

   A. in between the coil cases.

   B. at the coil case.

III. Specification of the main materials used for the backward support ring and the main support structure of the cryostat (cf. section 6).

IV. Upper limit for the permeability of not completely unmagnetizable materials (e.g. stainless steel screws) used for the coil cases, coil support and the forward support hexagon (cf. section 6.1.4).

V. Upper limit for the permeability of not completely unmagnetizable materials (e.g. stainless steel parts) used for the backward support ring (see Figure 1, cf. section 6.2.2).

2.4 Cryogenics

The specification of the cryogenic system should include the following topics:

I. Description of the liquid Nitrogen and liquid Helium cooling circuit. Description of the interface to the existing refrigerator system including liquid He parameters at the system input and exit point (temperatures, pressures and mass flow of ingoing and outgoing He)

II. Maximum consumption of liquid Helium and of liquid Nitrogen during steady state operation at full and at zero current. Verification method. The He mass flow through the current leads should be specified in addition.

III. Maximum consumption of liquid Nitrogen and liquid Helium during cool down from 300 K and 80 K, respectively.

IV. Description of the cool-down and warm-up procedures. Maximum time for cool down starting at 300 K and 80 K, respectively. Limitations imposed by the refrigerator capacitance should be mentioned separately.

V. Quench behavior at full current without any active quench protection and, in addition, with an external protection resistor to dump the field energy. Expected time dependence of the maximum coil temperature and of the coil current. Verification method. Helium loss at quench.

VI. Protection against refrigerator failures.

VII. Description of modifications of the existing liquefier, if necessary.

2.5 Power Supply

The power supply should be included as a separate option into the offer. However, GSI can provide a power supply including a circuit breaker and protection resistor. The specification of the interface to the power supply should include:

I. Current at full magnetic field.

II. Interface required for the control and monitoring system of the magnet.

III. Interface provided for the circuit breaker and protection resistor.

IV. Expected load of the external protection resistor during quench at full field.

V. Necessary protection against main power failure.

2.6 Monitor and Control System

The monitoring and control system for the magnet should be provided by the supplier. The offer should specify in particular:

I. Description of the monitor/control scheme.

II. Interface to an external global monitoring system (see section 10).

III. Specification of the interface to the liquefier system(see section 2.4 and section 8.6).

IV. Specification of the interface to the power supply (see section 2.5).

2.7 Tests and Commissioning

The supplier should specify:

I. Tests performed at the manufacturer site (including prototype tests).

II. Assembly procedure and tests performed at the GSI site. Field mapping will be performed by GSI but responsibility for alignment corrections of the coils (if necessary) is expected from the vendor.

2.8 Time Schedule

According to the time schedule for the other HADES components a time period of about 3 years is considered an upper limit for the detailed design, the manufacturing and commissioning of the magnet. A time schedule for the following four phases of the project should be provided (cf. section 14.1).

I. Detailed technical design.

II. Manufacturing of a full size prototype coil. In case the company has sufficient experience with this particular type of magnet including Al-stabilized superconductors, a prototype coil is not necessary.

III. Manufacturing of the coils and the cryostat at the company site. Tests at the company site.

IV. Transport and assembly of the complete system, test and commissioning at GSI. Technical support and manpower needed from GSI should be specified (see section 13.3).

2.9 Cost Estimate

The cost estimate should include the following topics:

I. Detailed technical design.

II. Manufacturing of prototypes, if necessary (see phase II described in section 2.8).

III. The complete system including:

- A. coils,
- B. cryostat,
- C. stands of the cryostat,
- D. transportation of the system to GSI,
- E. final assembly, testing and commissioning (cf. section 13.3),
- F. all sensors and monitoring equipment needed for the operation of the magnet.

IV. Excluded are:

- A. Power supply,
- B. control equipment for the power supply and refrigerator, cryogenic connection between cryostat and liquefier,
- C. Pumping system,
- D. field mapping,
- E. taxes as far as GSI is concerned.

The cost estimate should specify separately:

- A. Superconducting cable,
- B. manufacturing of coils including the internal coil support structure,
- C. cost estimate for a prototype coil, if necessary (see phase II described in section 2.8),
- D. cryostat,
- E. cryogenics interface,
- F. main support structure,
- G. monitor and control system,
- H. transportation, final assembly and commissioning.

In addition cost estimates for the items excluded (IV A,B) should be added:

- A. Power supply including circuit breaker and protection resistor,
- B. interface line to the refrigerator and modifications of the existing liquefier.

The cost estimate should indicate costs for material and labor.

2.10 Warranty

For the following items a warranty including a time period should be specified. A warranty time period of 3 years is requested:

I. The mechanical and electrical properties of the complete system,

II. quench survival without permanent damage even without any active quench protection like circuit breaker and dump resistor,

III. continuous operation of 6 month additionally to a stand-by period at 80 K of 6 month without exceeding the limits for the liquid Helium and liquid Nitrogen consumption (see section 2.4 and section 8),

The warranty should include:

I. service and repair work at the GSI site,

II. delivery of replacement parts which are not commercially available,

3 Geometry

3.1 Coils

3.1.1 Coil shape

The coil consists of two straight sections (entrance and exit section) connected via two arcs. The straight exit section covers a range of 22^{o} to 82^{o} . The "active" range on which particle tracking takes place covers a range of 18^{o} to 85^{o} (cf. Figure 5). A cross section of the coil is displayed in Figure 3. The origin of the coordinate system is at the center of the reaction target. The axis of hexagonal symmetry is equal to the z-axis.

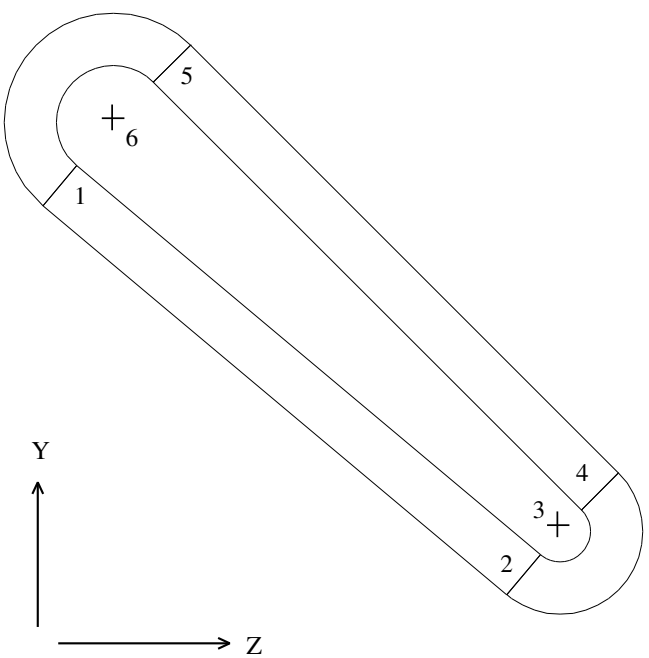

Figure 3: *Shape of the superconducting coil. See Table 1*

The location of the center of current of the coil is listed in Table 1. All dimensions refer to the warm condition of the coil (300 K).

No	Straight sections		Arcs : Center, Radius		
	Z [mm]	Y [mm]	Z [mm]	Y [mm]	R [mm]
1	-45.20	1289.10			
2	1105.11	323.86			
3			1192.47	427.41	135.16
4	1287.58	522.99			
5	225.77	1584.81			
6			83.82	1442.87	200.73

Table 1: *Geometry of the center of current of the superconducting coil.*

3.1.2 Current density and coil cross section

The current/coil amounts to **485000 A*turns**. The magnetic field and corresponding forces are discussed in section 5.1 and section 5.3, respectively.

Two examples are given in Table 2 in order to estimate the current densities and coil cross sections . A fraction of 15% of the coil is assumed to be used for the insulation of the cable. For the first example,

the peak field amounts to ~3.55 T, for the second one to ~3.75 T, respectively. In the first case, the support structure (10 mm) was put in between two twin coils (cf. Figure 14). In order to limit the current to reasonable values around 3500 A (see section 12) about 140 turns (e.g. 4 times 35 turns) of the cable could be used.

coil size [mm^2]	ratio Al : Cu Nb Ti	average current density A/mm^2	current density in Nb Ti A/mm^2
2*15 * 130	2.8 : 1	124.4	556
35 * 130	3.25 : 1	106.6	533

Table 2: *Examples for coil cross sections and corresponding current densities.*

3.2 Cryostat

3.2.1 Definition of „Keep in“ zones

In the following sections „Keep in“ zones of the cryostat are specified. For additional elements attached to the cryostat (breaking the azimuthal hexagonal symmetry) like the cryogenic interface or vacuum flanges „Keep out“ zones are defined. These zones refer to the symmetry axis of the magnetic field. They include tolerances if not explicitly stated otherwise (width of the coil case). All elements should stay within the „Keep in“ zone or outside the „Keep out“ zones regardless of the mode of operation i.e. cold and warm system at zero and at full field.

3.2.2 Volume needed by the inner tracking detectors and the RICH detector.

In the midplane of the coil the following area should be reserved for the tracking detectors (see Figure 4): The region limited by a -40^o line parallel to the straight entrance section of the coil at a distance of

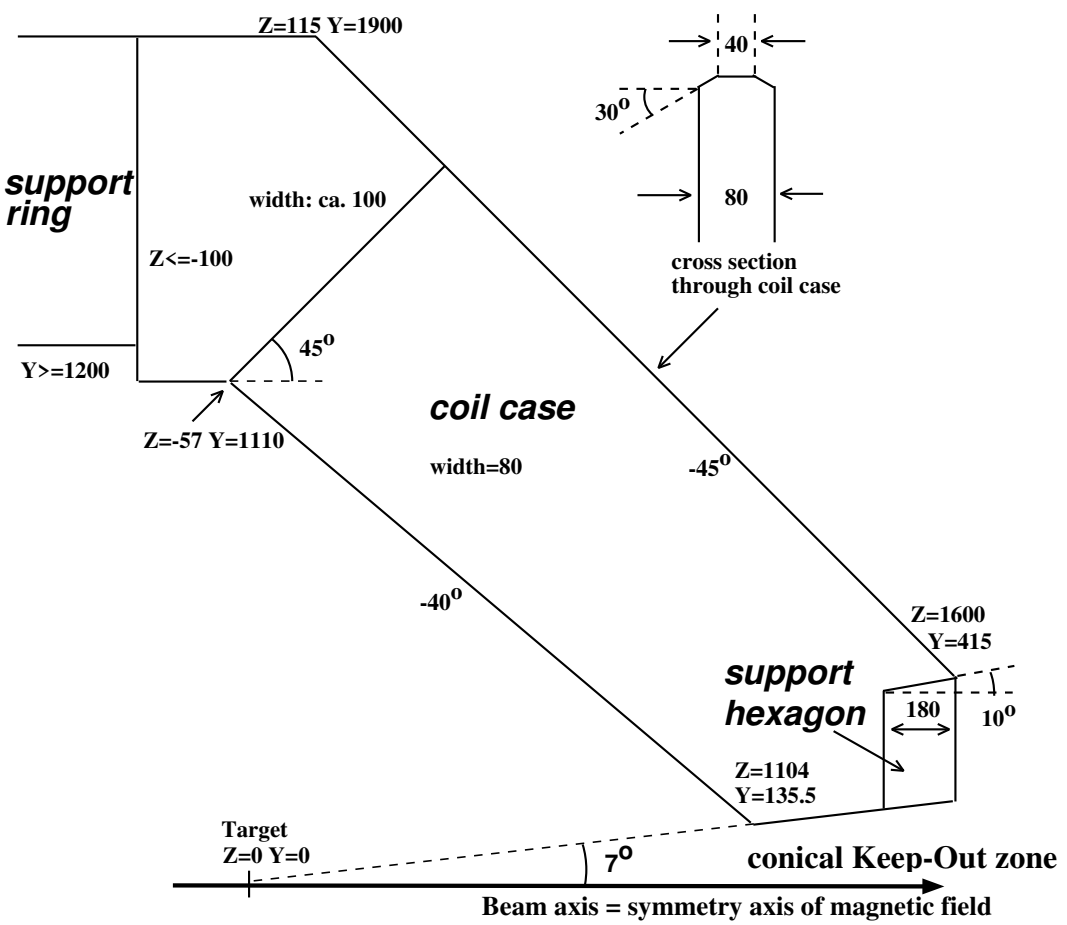

Figure 4 : *"Keep in" volume of the coil case and the support structure connecting the coil cases.*

145 mm or less from the center of the coil. With the exception of the (circular) outer support ring and the conical bore of the support hexagon, the cross section perpendicular to the area shown in Figure 4 forms a hexagon. The corners of the hexagon are located at a distance of 1110 mm perpendicular to the beam axis at -57 mm upstream of the target position (see Figure 4 and Figure 5).

3.2.3 Volume needed by the outer tracking detectors.

The outer tracking detectors will surround the coil cases forming a hexagon. Thus, the coil cases should clear a line at -45° parallel to the straight exit section of the coil at a distance of 145 mm (or less) from the center of the exit section of the coil (see Figure 5). Behind the tracking chambers (at negative z-values between -100 mm and 0 mm) additional space is needed for the readout electronics and detector support. Any flanges which might be used to get access to the coils must be located within the region z < -100 mm if they stick out of the „keep in" zone described in Figure 4. These flanges should be kept as compact as possible. In particular, they must be specified by engineering (scale) drawings and GSI must explicitly agree to their location and shape.

It would be helpful for the design of the tracking detectors if the coil cases could be more compact than specified by the numbers mentioned before (cf. section 3.2.5).

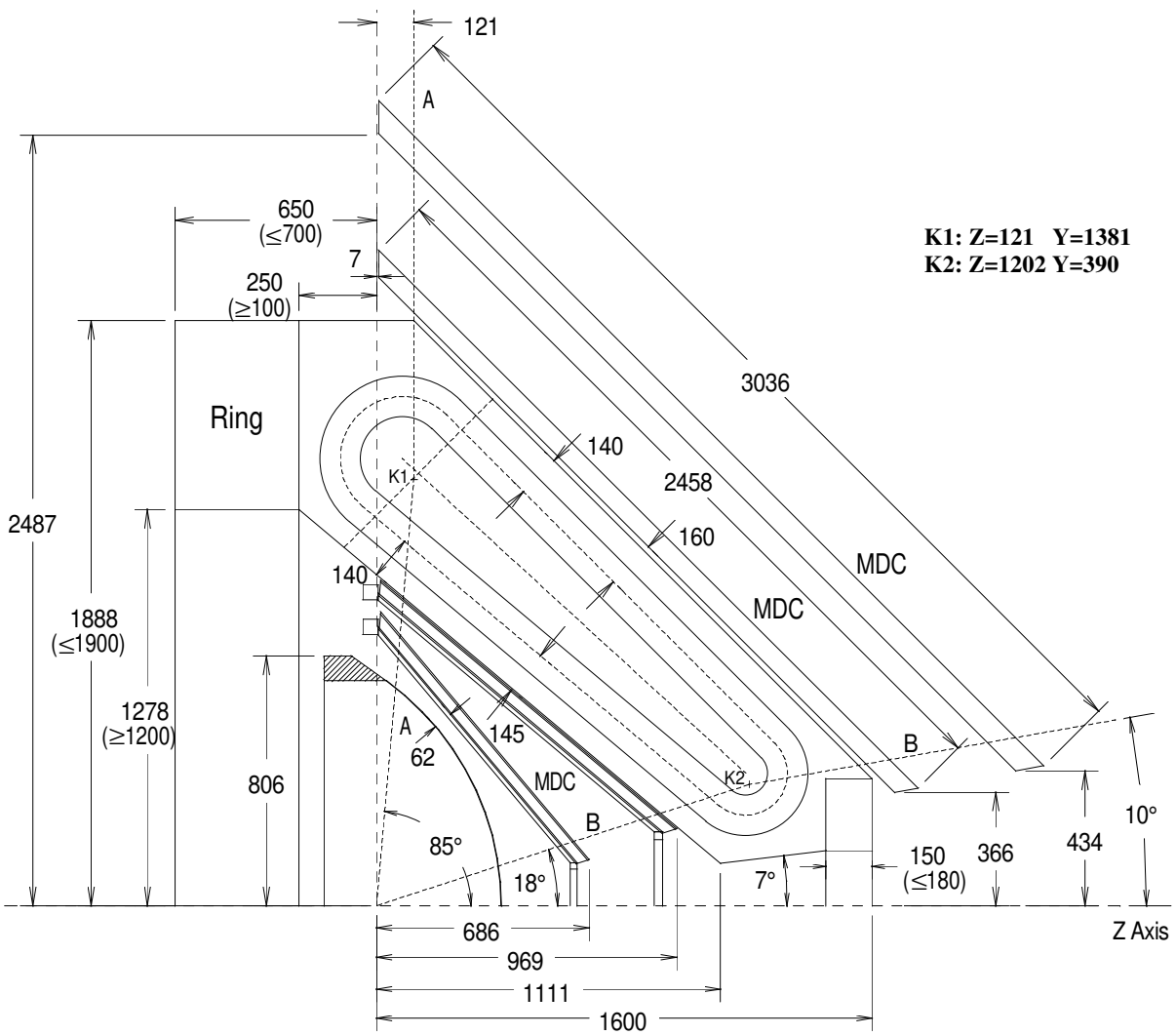

Figure 5: *Proposed positions of the HADES Detectors with respect to the Torus coils and coil cases. Cut through the coils. The dimensions of the cryostat refer to a particular design used in performance simulations.*

3.2.4 Volume allowed for the support of the coil cases

The forces onto each coil must be compensated by connecting the coils and/or coil cases with each other directly in front of the coil. The space available for this connection forms a hexagon and is labeled "support hexagon" in Figure 4 .The support structure behind the coils (labeled "support ring" in Figure 4) should allow to move the RICH detector and the inner tracking detectors (MDC's) horizontally into and out of the system. This requires access within a region of 1200 mm radius („Keep out" zone, see Figure 6). The outer support ring should be located behind the target (at negative z values, $z \leq -100$ mm). It should not extend backwards beyond a value of z = -700 mm. Flanges for the turbopump or for vacuum gauges are excluded from this limit.

The arrangement of the tracking detectors with respect to the coils, coil cases and support structure is shown in Figure 1 for a vertical cut (in between the coils). The coils and coil cases are projected into the vertical plane. Figure 5 shows the positions of the tracking detectors more quantitatively for a horizontal cut (through the coils). The dashed lines labeled „A" and „B" in Figure 5 display the boundaries of the volume in which particles are tracked (e.g. active areas of the tracking detectors).

3.2.5 Width of the coil case

The solid angle (width / radial distance from the beam axis) covered by the vacuum chambers of the coils should be kept small. The current design of the whole setup is based on a solid angle which corresponds to a total width of a vacuum chamber of 80 mm (see Figure 4). This thickness should not be increased at least at polar angles between 18^o and 45^o. The specified width of 80 mm does **not** include positioning tolerances. They are discussed separately in section 7.2 . At large polar angles (backwards of the 45^o line starting at z = -57 mm in Figure 4) a width of about 100 mm is acceptable. Backwards of the tracking volume defined by line „A" in Figure 5 an even larger width of the coil case of up to 150 mm is tolerable. In all cases, the outer edge of the coil case should stay within the region defined by the 30^o lines in the insert of Figure 4. If the coil case is azimuthally not centered with respect to the coil it must stay on either side within the limits specified above for the symmetric case.

Below the entrance section of the coil a conical cross section would reduce the solid angle covered by the coil case. However, any design which yields a significant reduction (>4%) of the solid angle covered by the coil case below the limits specified above and in Figure 4 should not result in a cost increase by more than about 2%.

3.2.6 Cryogenic connections, power leads

The cryogenic connection to the refrigerator should be placed on top of the outer support ring (see Figure 6). Its height should not exceed 6 m. The current leads can also be placed on top of the support ring. The limit of 6.0 m total height applies for the current leads as well. Since the total height of the system determines the height of the cave in which the setup is located, a more compact system (height < 6m) would reduce the cost for the concrete shielding considerably.

Both, the cryogenic interface as well as the power leads must be placed at a location $z < -100$ mm. Components of these interfaces located above the outer support and interface ring can extend backwards beyond the limit of Z =-700 mm requested for the ring itself.

3.3 Support Structure

The whole cryostat should be positioned by a support structure (stands) such that the magnetic-field symmetry-axis of the system runs horizontally at a distance of 2.5 m above the floor. Any element of the support of the cryostat should be placed behind the target position ($z \leq -100$ mm, see Figure 4 and Figure 6). The support structure should further clear the „keep out" cylinder around the z axis (diameter = 2400 mm) shown in the right part of Figure 6.

The Mini-Drift Chambers (MDC's) as well as the Time-of Flight scintillators and the Shower detector are kept in position by their own support structure (c.f. Figure 2). The outer detectors can be moved sectorwise in beam direction, the inner MDC's form hexagons which can be moved backwards on rails.

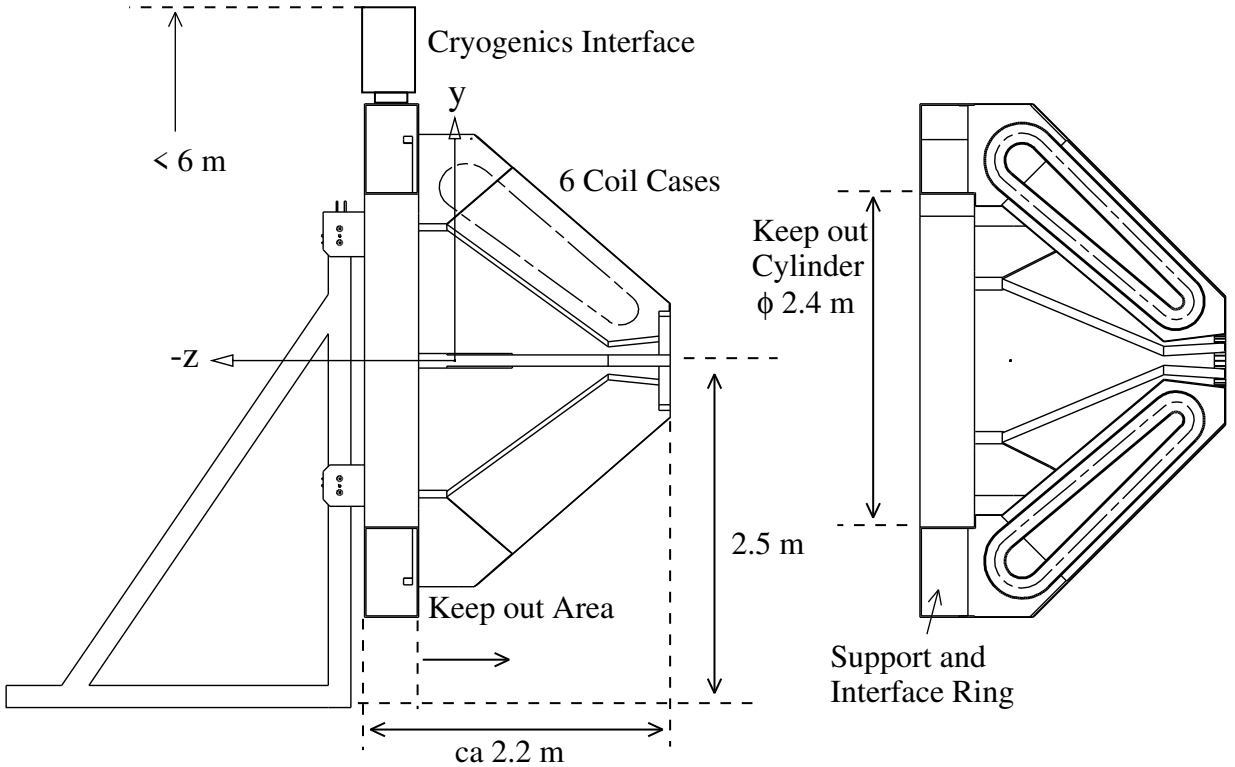

Figure 6 : *Vertical (left) and horizontal (right) cut through the magnet including schematically coil cases, support ring and front support hexagon.*

A schematic front view of the torus without cryogenic interface is shown in Figure 7. It shows in particular the azimuthal location of the coils and the shape as well as the orientation of the forward support hexagon. The details of the drawing should be considered as an example only. A three-dimensional view of the support structure of the detectors is displayed in Figure 2.

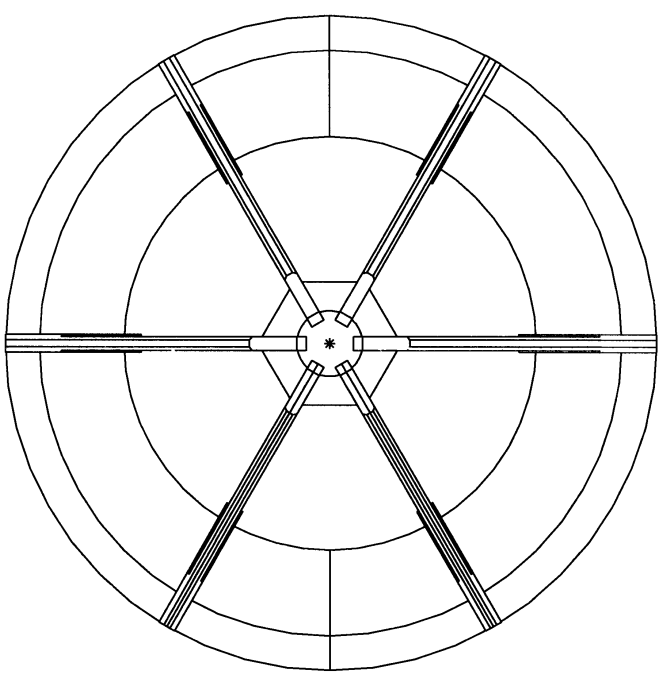

Figure 7: *Schematic front view of the torus.*

4 Mode of Operation

The magnet will be operated in DC mode. A change of the current will take place on the average about once or twice within a week during a time of operation of typically 3 months per year. During the remaining time the system will be in a stand-by mode kept at 80 K. The system will be operated over an anticipated period of 10 years. The following list specifies the requirements resulting from the anticipated mode of operation:

I. The system must be capable of operating with either magnetic field polarity. The switching can be done by exchanging busbar connections at the power supply.

II. The charge-up time from zero to full current should not exceed 4 hours.

III. The system must allow at least 1000 charge-up cycles from zero to full current.

IV. The system should allow cool- down and warm-up periods from 300 K to 4 K of 10 days or less. The cool down period from 80 K to 4 K should be less than one day. Expected limitations related to the capacitance of the refrigerator should be stated separately.

V. The system must withstand 100 cool-down/warm-up cycles (300 K to 4 K).

VI. Operating temperatures will range typically from 20^{o} to 30^{o} C, during the standby time the temperature can vary from 15^{o} to 30^{o} C.

5 Magnetic Field

5.1 Field Maps

Contour Plots of the magnetic field at different azimuthal angles are shown in Figure 8 to Figure 10.

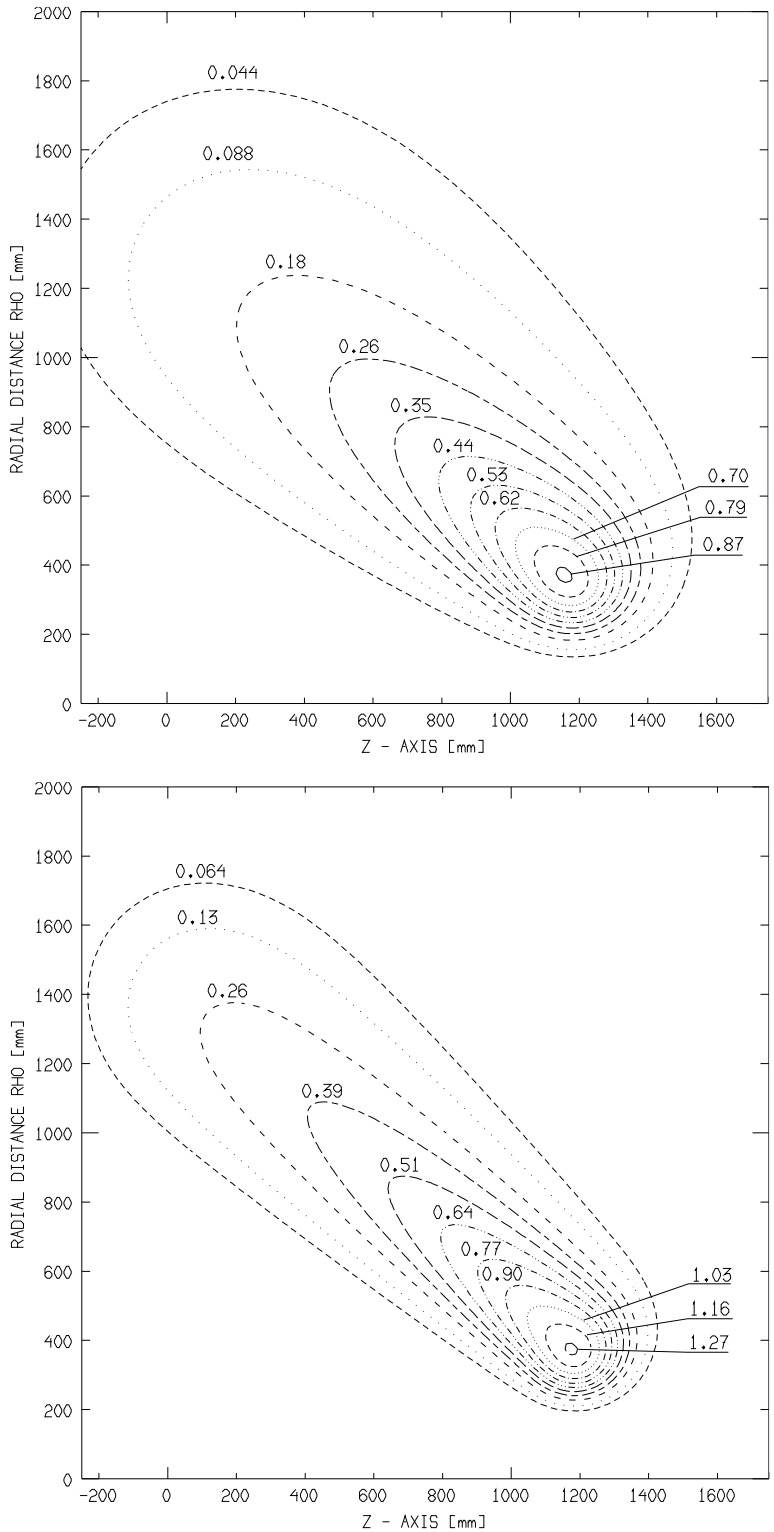

Figure 8 : *Main magnetic field component B_ϕ in between 2 sectors at an azimuthal angle of 0^0 (top) and at an azimuthal angle of 15^o (bottom), respectively. The field strength is specified in Tesla.*

The field map was obtained for the coil shape of example 1 in table 2. The total energy stored in the magnetic field amounts to 1.4 MJ.

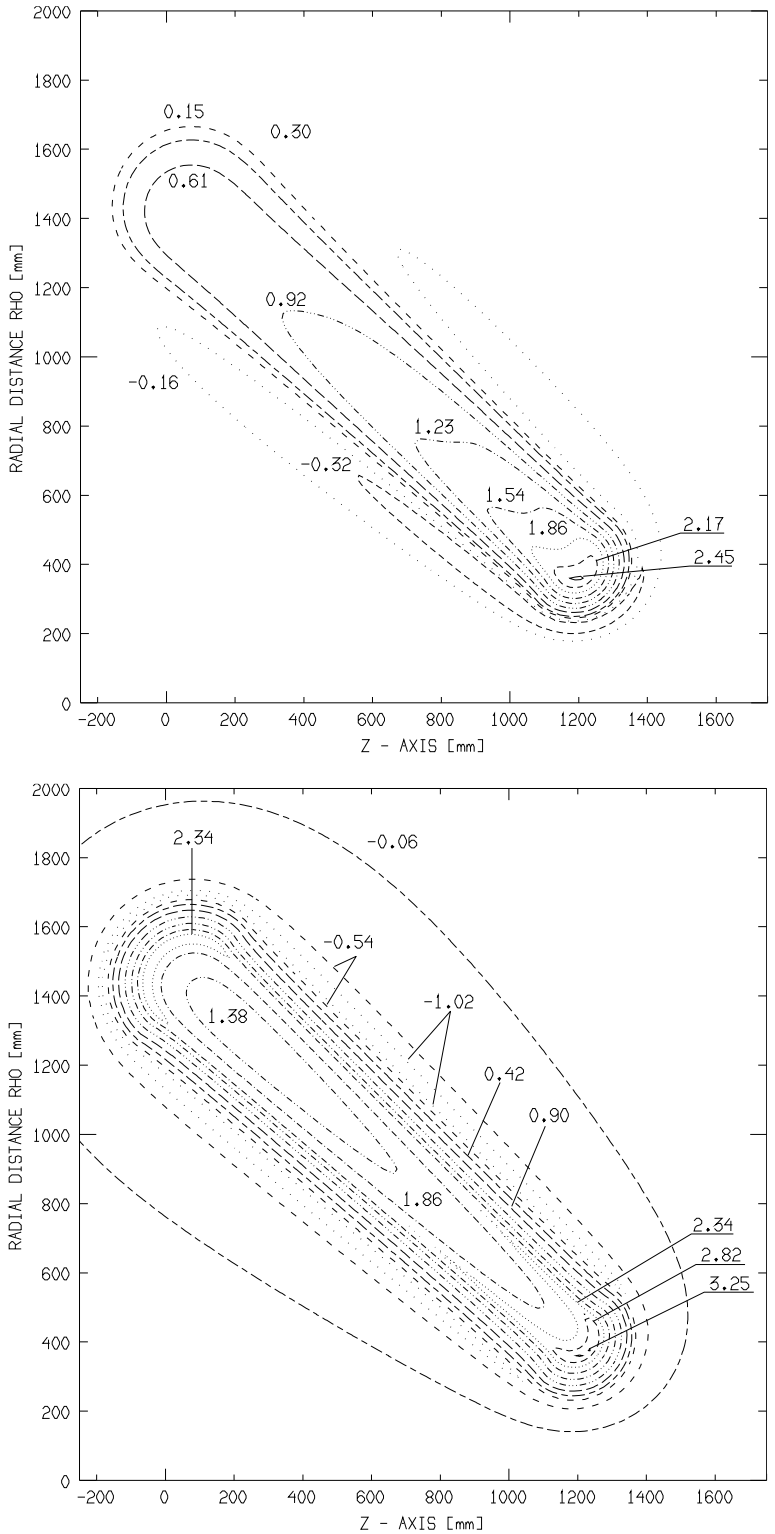

Figure 9: *Main magnetic field component B_ϕ at an azimuthal angle of 25^o (top) and 30^o (bottom), respectively. The field strength is specified in Tesla.*

5.2 Peak Field

The peak field amounts to 3.55 T for the coil example 1 and 3.75 T for example 2 of Table 2, respectively. The magnetic field reaches its maximum at the inner part of the arc connecting end-points

2 and 4 of the straight sections (see Figure 10). The actual value of the peak field depends on details of the coil shape. It could be reduced by introducing an arc of pure aluminum in between the inner and outer half of the coil as shown in Figure 11.

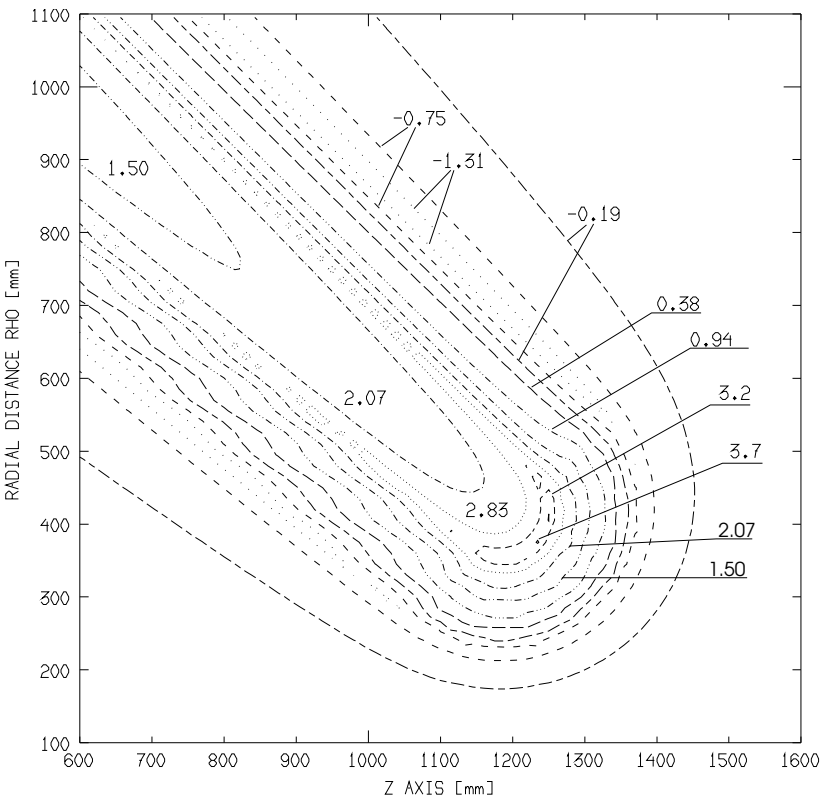

Figure 10: *Field map in the midplane of the coil (130*35 mm^2). Only the high field region is shown.*

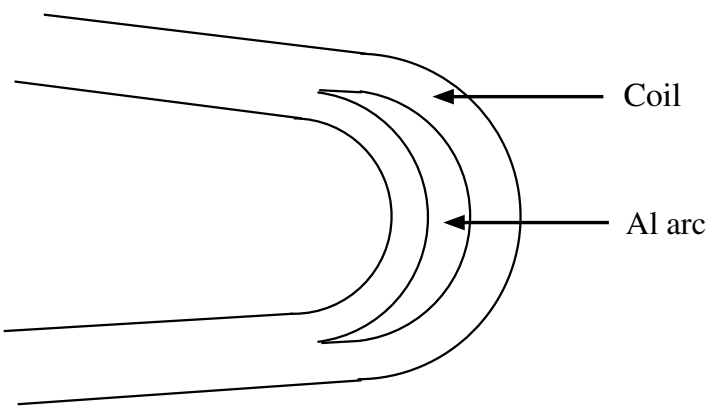

Figure 11: *Optional reduction of the peak magnetic field by inserting an Al arc in the forward part of the coil.*

5.3 Forces

The differential forces on the coil due the magnetic field are shown in Figure 12. The net force on a single coil amounts to 4.7 t - 4.9 t depending on the coil design. The net forces on the coils can be compensated either by a common cold support in front and behind the coils or by connecting each coil individually to its coil case. A ring and a hexagon behind and in front of the coil cases compensate the forces (see Figure 1 Figure 4, Figure 5 and Figure 7, respectively).

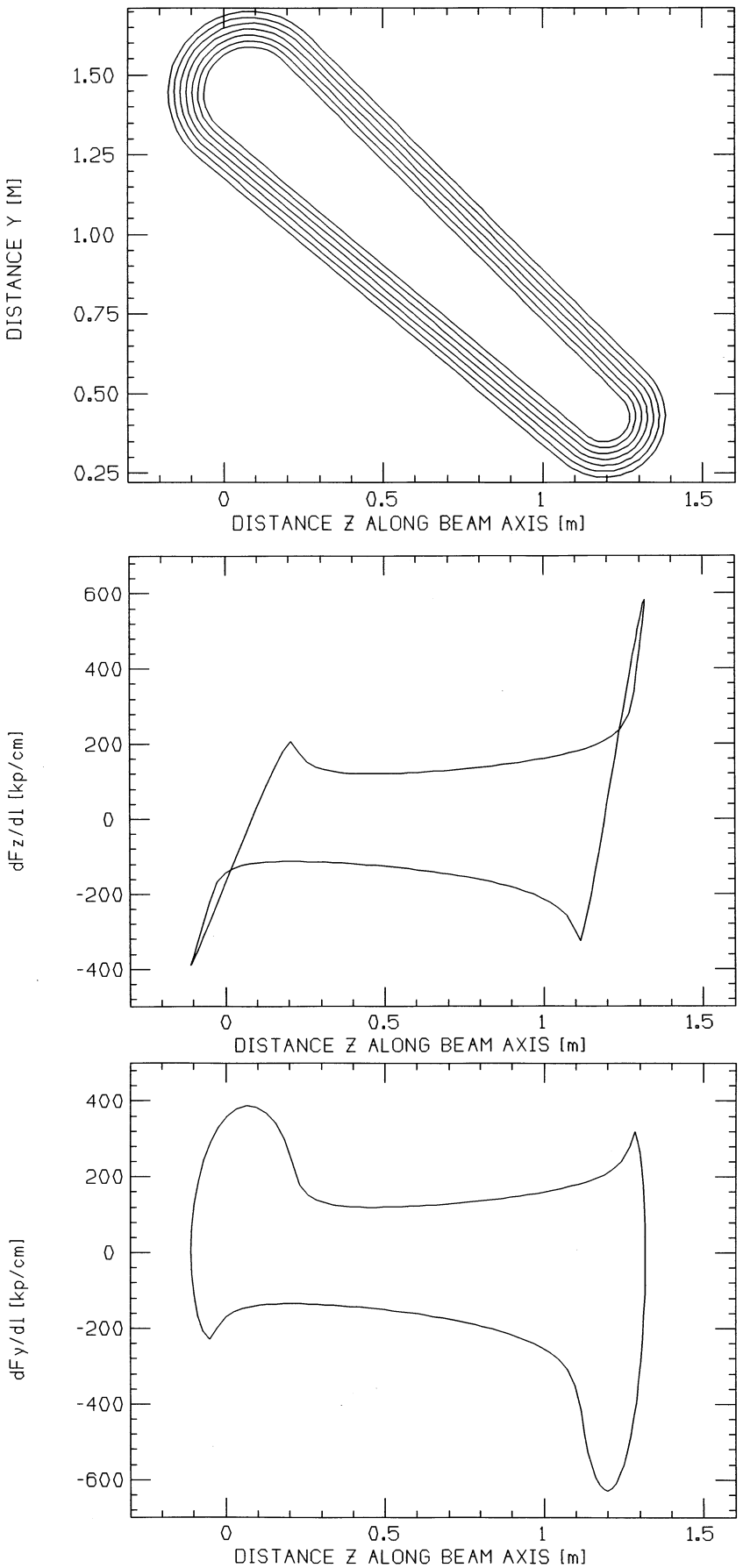

Figure 12 : *Coil shape (top) and differential forces dF_z / dl (center) and dF_y / dl (bottom) along the coil (dl).*

6 Materials

6.1 Coils and Coil Case

6.1.1 Definition of an effective thickness

The material of the coil case and the coils in the region below polar angles of 85° must fulfill certain constraints in order to keep the production of secondary particles low. These constraints can be defined by an effective thickness d in terms of radiation length. The effective thickness can be determined in the following way:

The cross sections of the various components of the coil case and the coils within the straight section are divided by the radiation length of the material of the respective component. These effective component thicknesses are summed over all components. Discrete components such as fixings, bolts etc. must be accounted for by taking their total volume and dividing it by the length of the respective zone (1 -5) to calculate an effective cross section.

The final total thickness d_{tot} is obtained by summing over all coils. This number should not exceed a value of

d_{tot} = 2600 mm above polar angles of 45° and

d_{tot} = 2500 mm below 45°, respectively.

In particular, at small polar angles this effective coil thickness should be as small as possible.

The effective thickness as defined above should be obtained on the average in each subdivision of the coil and coil-case area defined in Figure 13. According to the limits specified above d_{tot} should not exceed 2600 mm in area 1 and 2 and $d_{tot} \leq 2500$ mm in area 3 and 4, respectively. In the region of the

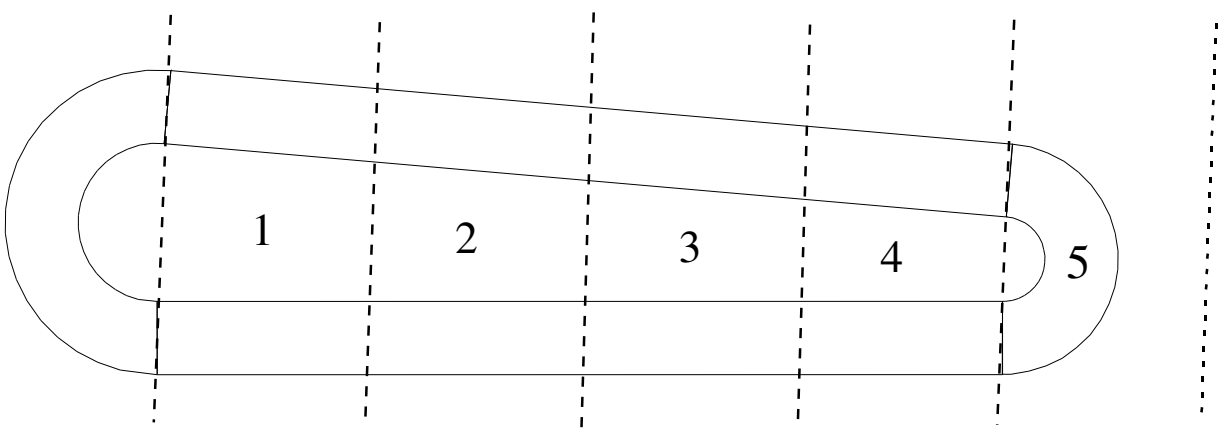

***Figure 13**: Subdivision of the coil and coil-case area into 4 sets with equal width and the region of the forward arc (5).The left (right) limit of zone 1 (4) passes through the center of the corresponding arc (see Table 1).*

forward arc (5) any additional material needed e.g. to keep the coil in position should be placed in front of the arc. Taking the same thickness of 80 mm for zone 5 and the same width (app. 340 mm) as for area 1-4 the limit of d_{tot} = 2500 mm applies for zone 5 as well.

6.1.2 Estimate of the effective thickness of the coil

In the following examples a superconductor with a ratio of Cu : Nb Ti of 1.4 : 1 is assumed. The ratio of Nb : Ti is assumed to be 1 : 1.1. Taking the examples of Table 2 the following values are obtained (crude estimates):

First example of Table 2, coil only:

component	area [mm]^2	radiation length [mm]	effective thickness [mm]
Al	2442.6	89	27.4
Cu	511.9	14.3	35.8
Nb	174.1	ca. 12	14.5
Ti	191.5	35.6	5.4
insulation	585	ca. 160	3.7
Sum			**86.8**

Table 3: *Coil cross section normalized to the radiation length of the various materials.*

Summing over the entrance and exit section of the coil and over 6 coils gives:

$$\mathbf{d_{coil} = 1041\ mm}$$

and for example 2 of Table 2:

$$\mathbf{d_{coil} = 1142\ mm}$$

The effective thickness is mainly given by the amount of copper inside the coil.

6.1.3 Estimate of the effective thickness of the vacuum chamber, coil support and shield

Assuming that the vacuum chamber consists completely of aluminum and taking only averaged values for the sizes and areas of the vacuum chamber, the shield and the support structure the following crude estimates give a feeling for the contribution of these components to the total effective thickness:

component	size [mm]^2	area [mm]^2	effective thickness [mm]
coil support plate	440*12	5280	59.3
80 K shield	2*480*2	1920	21.6
vacuum chamber side walls top, bottom	2 * 580*6 2 * 20*68	9680	108.8
sum			**189.7**

Table 4: *Example of the effective thickness of the coil case, LN_2 shield and coil support obtained at a polar angle of about 45^o.*

Summing over 6 coils, gives the following effective thicknesses for coil case, shielding and coil support:

$$\mathbf{d_{chamber} = 1138\ mm}$$

The total effective thickness (including the coil) amounts to:

2179 mm and **2280 mm** for coil example 1 and 2, respectively.

The effective thickness of the support structure, the shield and the vacuum chamber is of the same order as the effective thickness of the coil itself. The contribution of the side walls of the vacuum chamber to the total thickness (including the coil) amounts to 18%. Obviously, a fancy sandwich structure of the chamber alone would not decrease the total effective thickness distinctly. The above examples are given only to illustrate the calculations which are needed. The detail design work must account for all components of the coil structure including e.g. cooling pipes as well as all discrete parts (e.g. bolts) of the vacuum case.

A schematic view of a possible arrangement of the coil, support structure and LN_2 shield within the vacuum chamber is shown in Figure 14. Optional spacers between the side walls of the vacuum chamber have been assumed present in estimating the thickness of the vacuum case. The two schemes differ by the arrangement of the He pipes and should be considered as examples only.

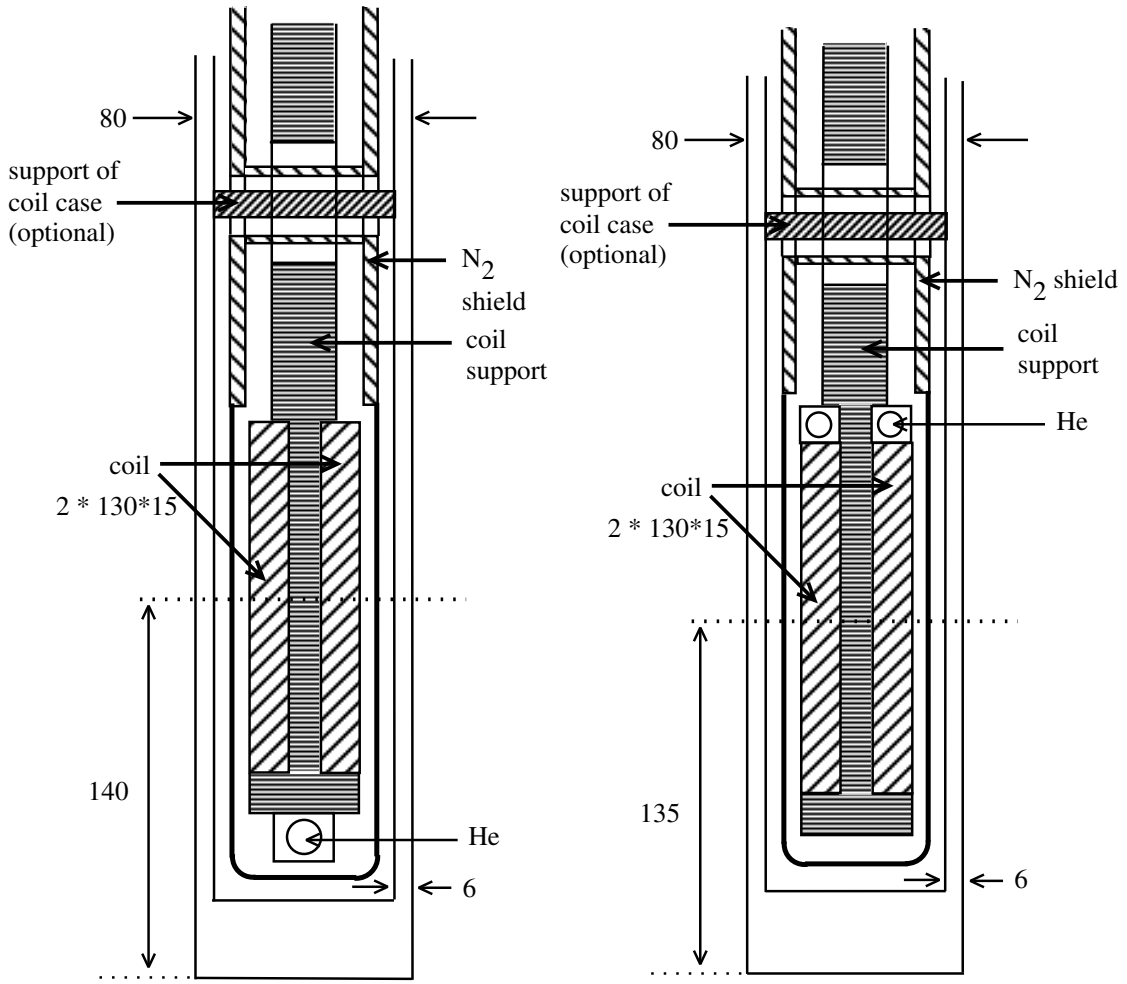

Figure 14 : *Schematic cross sections through a coil case including coil, support structure and LN_2 shield. Dimensions and shapes should be considered as examples only. An intermediate support of the sidewalls of the coil case is assumed (but not mandatory) to minimize there thickness.*

6.1.4 Magnetic properties

The permeability μ, in particular of stainless steel, should not exceed a value of $\mu = 1.05$ averaged over a volume of 4 cm^3. The hexagonal symmetry should be maintained for all materials with permeabilities larger then $\mu = 1.01$.

6.2 Support Structure

6.2.1 Effective thickness

Below a polar angle of about 7^o, no material should be placed. Between polar angles of 7^o and 16^o the total thickness of material averaged over all azimuthal angles in between the coil cases should not exceed 0.5 radiation length.

At polar angles larger than 85^o there are no particular limits with respect to the effective thickness of the support structure. However, the thinner, the better.

6.2.2 Magnetic properties

The permeability, in particular of stainless steel, should not exceed a value of $\mu = 1.05$ averaged over a volume of 5 cm^3 for the forward support hexagon and averaged over 10 cm^3 for the backward support ring. In particular welded joints should stay within this limit. The hexagonal symmetry should not be violated with respect to all materials with permeabilities larger then $\mu = 1.01$. Backwards of the outer support ring the requirements are less stringent ($\mu < 1.1$ averaged over 100 cm^3, no symmetry requirements).

6.3 Radiation Damage

The expected radiation is low enough to allow even conventional electronics to be mounted directly inside the torus. No particular constraints concerning the choice of materials are expected with respect to radiation damage.

6.4 Material Quality and Standards

All materials used for the coils, coil support, cryostat, cryostat support, sensors and connectors should fulfill the following constraints:

I. All materials should be free of corrosion under the usual atmospheric conditions.

II. Raw materials should be specified according to standards defined by DIN 50049/2 or 3b (This is a common specification sheet concerning the material composition which does not impose any particular constraints)

III. The surfaces of all vacuum vessels, shields, coils, and coil support must have a quality such, that the liquid He and liquid Nitrogen consumption are not severely affected by a reduced quality of the thermal shielding caused e.g. by outgasing.

IV. All materials must be clean, in particular free of dust and other particles to which they might have been exposed during the manufacturing process. Furthermore, oil or other liquids used for machining purposes must be removed by non aggressive solvents of high purity.

V. Vacuum sealings based on VITON or NEOPREN can be used as far as other constraints specified e.g. in section 8.4 and 8.5 are not affected by the choice of the sealing material.

VI. As far as possible, all welded joints should be located at the vacuum side of the cryostat. If additional welded joints are needed at the outside of the vessel e.g. in order to fix the position of components, gaps must be foreseen in between the welded joints to avoid air filled volumes completely enclosed by material.

VII. All screws should have metric threads. Non magnetizable material must be used within the field region (see section 6.1.4 and 6.2.2).

VIII. All removable connections (flanges or connectors) between different parts of the system must be based on well established standards. GSI must explicitly agree to the choice of the flanges in case of the vacuum (c.f. section 9) and the cryogenic system.

IX. As far as possible, electrical and thermal insulation should be based on materials free of Halogenides like Cl.

7 Alignment

7.1 Alignment of the Coils

An azimuthal misalignment of the coils with respect to the hexagonal symmetry destroys the field symmetry between the 6 sectors. The maximum azimuthal deviation of the coils with respect to the hexagonal symmetry should not exceed $\pm$ 2.0 mm at polar angles θ above 45° and $\pm$ 1.5 mm below 45°,

respectively. This misalignment results in a variation of the field integral within the tracking region of less than 0.4%. The azimuthal spacing between neighbored coils should not deviate from the ideal hexagonal symmetry by more than 2.5 mm ($\theta > 45^o$) and 2.0 mm ($\theta < 45^o$), respectively. The latter represents a limit on the misalignment correlation. The radial misalignment of the coils with respect to each other should not exceed 0.5% of the radial distance from the beam axis. The alignment accuracy of the coils refers to the cold system only. The reproducibility of the coil positions after warm up and cool down should be better than the values mentioned above by a factor of 4.

The system must withstand any forces resulting from asymmetric coil positions within the alignment limits specified above and in section 7.2.

The proposed method of verification of the relative coil alignment is via mapping of the magnetic field. A set of about 32 reference points in each of the 6 sectors should be sufficient for this purpose.

7.2 Alignment of the Cryostat

The symmetry axis of the cryostat should not deviate from the symmetry axis of the magnetic field by more than 2 mm for the forward support hexagon and by more than 5 mm for the outer support ring. The coil cases must maintain the ideal (hexagonal) symmetry within 0.5% of the radial distance from the symmetry axis defined by the magnetic field or within 2 mm (whichever number is larger). The azimuthal position of the coil cases should not deviate from the ideal hexagonal symmetry by more than 2.5 mm at large polar angles $\theta > 45^o$ and by more than 2 mm at $\theta < 45^o$. In addition, the azimuthal spacing of neighbored coil cases should not deviate from the ideal hexagonal symmetry by more than 2.5 mm at $\theta > 45^o$ and by more than 2 mm at $\theta < 45^o$, respectively. The twist between the forward and the backward part of the coil case should not exceed 2 mm. These alignment limits should be fulfilled independently of the mode of operation (e.g. with zero / full magnetic field, at 300 K as well as at 4 K coil temperature).They should be maintained within a temperature range from 20^o to 25^o C. These constraints are additional to the „Keep in zones“ specified in section 3.2 .

The main support structure of the cryostat should allow to align the whole cryostat in all three dimensions with an accuracy and reproducibility of 0.5 mm. In particular the alignment procedure must allow to adjust the direction and position of the magnetic symmetry axis with respect to a given „beam axis“ within a range of at least 0.2^o and ±15 mm, respectively. The outer support ring as well as the forward support hexagon should contain special reference points which allow to control the alignment by optical methods. The alignment accuracy of 0.5 mm must be maintained only for the cold system, the warm or vented system can show considerable deviations as long as it stays within the „Keep in“ zones. An additional variation of the alignment as a function of temperature should not exceed 0.5 mm within a temperature range of 20^o to 25^o C.

The alignment should not be affected within the accuracy specified above after an intermediate mechanical load of 50 kp was applied to the system (e.g. during the detector assembly or service work) from inside (region around the target) or outside (region of outer tracking detectors, front, rear side). The sidewalls of the coil cases must withstand a temporary, local mechanical load of 20 kp, maintaining the specified alignment afterwards. The system must withstand the loads resulting from usual assembling, operating and maintenance procedures without requiring realignment afterwards. A typical assembling procedure is e.g. the mounting/dismounting of flanges.

The forward support hexagon should contain 6 (maximum 12) threaded holes (diameter ≥ 6 mm, M6) which can be used to attach a central vacuum chamber. The load of this chamber onto the support hexagon will stay below 30 kp. A variation of this load by 20% should not affect the alignment.

8 Cryogenics

8.1 Existing Liquefier

GSI owns already a He liquefier plant. It is the model TCF 20/DSB 200 manufactured by Sulzer. In Figure 15 this plant is described schematically. In order to match the needs of the magnet, this system needs modifications discussed in section 8.2 and 8.3 .

Existing Plant TCF 20/DSB 200 (schematically)

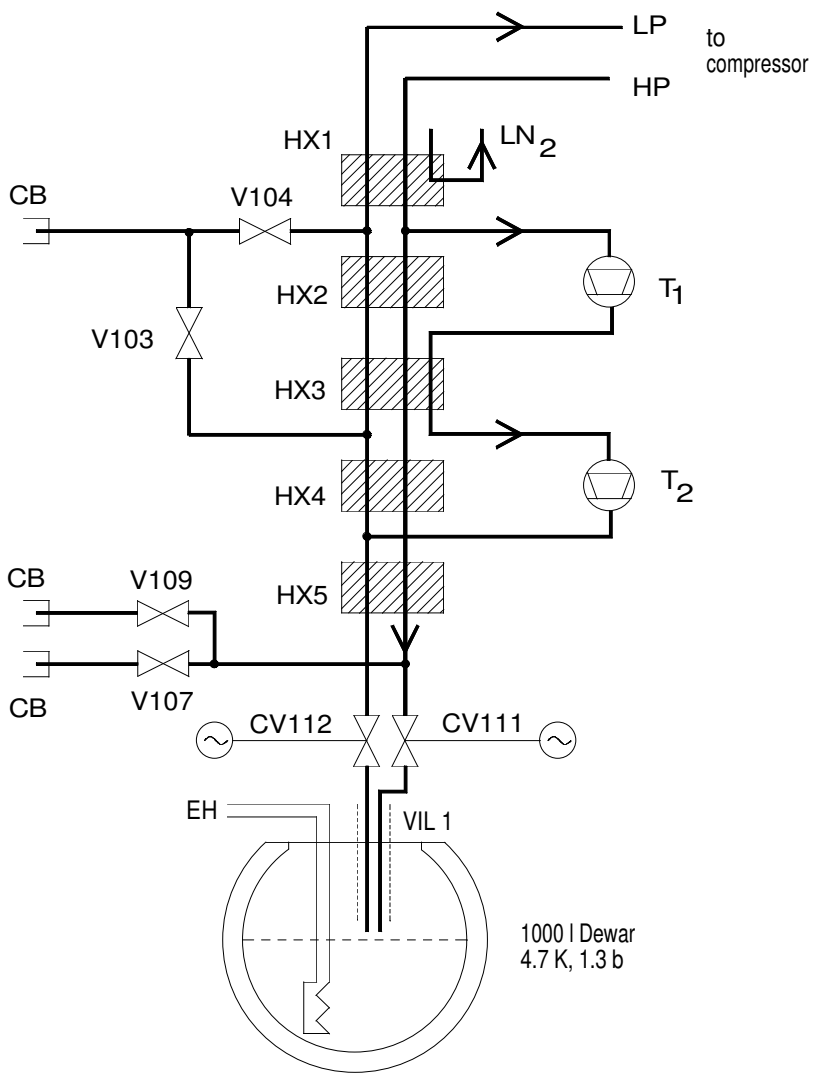

Figure 15: *Existing He Plant. HP = High pressure (10.3 bar), LP = Low pressure (≅ 100 mb, HX = Heat Exchanger, V = Valve, CV = Controlled valve, CB = Cryogenic bayonet, T = Turbine expander, VIL = Vacuum insulated line, EH = Electric Heater.*

8.2 Proposed Modifications

In order to use the existing liquefier in a refrigerator mode with forced flow, single phase He cooling the magnet the scheme shown in Figure 16 is proposed. In the following, a short process description is given for that scheme.

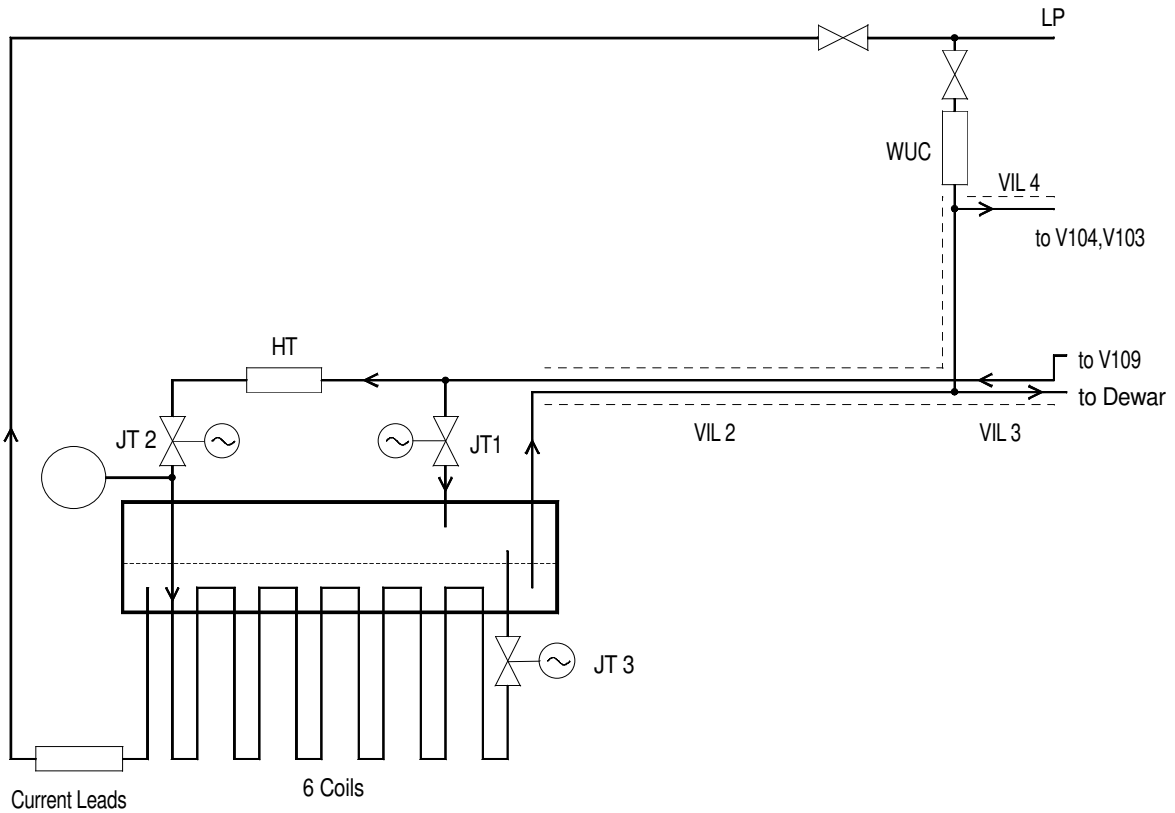

Figure 16: *Proposed Modification of the liquefier for forced flow cooling of the magnet. HT = Electric Heater, WUC = Water cooled warm-up coil, JT = Joule Thomson valves, VIL = Vacuum insulated line.*

8.2.1 Normal service

7 K gas at 10.3 bar (5.9 K to be confirmed) leaves the plant via valve V107 and the existing cryogenic bayonet. It is fed through the cryogenic transfer line VIL (ca. 10m) into a cryogenic unit close to the coils. Here a fraction is expanded to 1.3 ata in order to produce 4.7 K liquid in a heat exchanger unit. The rest of the mass flow is expanded to 2.8 bar and subsequently in the exchanger unit cooled to 4.7 K. This single phase gas cools the 6 coils in series and at the end is expanded to 1.3 ata. Part of the liquid is removed to cool the current leads and returns warm to the LP-side of the plant. Two phase 1.3 ata 4.7 K helium returns through VIL 2 and VIL 3 to the 1000 l storage dewar. The liquid collects there and the vapor returns through CV112 into the return stream of the heat exchanger column. (CV111 remains closed)

An existing heater can keep the level constant in the dewar.

Since the flow through the turbines can be controlled only in a very limited range, which means more or less constant cooling power, it seems very unlikely to make a definite temperature, pressure and mass flow at the entrance to the coils by one single Joule Thomson-valve (JT2).

Since all the losses on the 4 K level (HP and LP return) add to the heat losses of the coil much care has to be taken for the design of the cryogenic transfer lines VIL2, VIL3 and a possible replacement of VIL1. A nitrogen cooled shield or an intermediate temperature helium cooling seems to be stringent. It should be discussed if VIL4 is blanked after cooldown since those open tubes bear the danger of oscillations and uncontrolled heat losses.

For a possible power failure of the plant a buffer volume at 2.8 bar sufficient for the period of discharging the coils is necessary.

8.2.2 Cool down

The helium flow is as in normal service, but JT2 and JT3 are fully open, JT1 is closed, V112 is closed. From 300 K to about 120 K only nitrogen cooling is used in HX1 (turbines stopped). The gas returns to the plant through VIL4 and enters through V104 to HX1. The cooling speed is limited by the pressure drops and the temperature differentials allowed by the thermal stresses in the coils.

At lower temperatures the turbines are started and cooldown proceeds smoothly. Since the cooling power is very hard to regulate it is unavoidable to add a 1500 to 2000 W controlled electric heater into the gas stream in order to prevent large temperature steps at the entrance of the coils.
In a later stage the cold return gas is injected through V103 into a cooler part of the heat exchanger column. Stored liquid in the dewar can be evaporated to increase the cooling capacity.

8.2.3 Warm up

A simple method could be breaking the insulating vacuum of the coil cases in a controlled way. Even if pure N_2 is used for that purpose, this may cause bad conditions for the detectors by attracting moisture from the air and even dropping water when the surface temperature is below the dew point. Thus, such a method should be avoided.
It is proposed to perform the warm up in an analogous way as the cool down. In order to prevent excessive frosting of the return lines it is suggested to add a water cooled warm up coil before the gas is returned into the LP line.

8.3 Thermosyphon Cooling

A thermosyphon cooling method is acceptable as well. It might require to mount the system such that no coil is in a horizontal position (system rotated by 30^o). This results in a larger height of the beam line (app. 2.9 - 3 m) and the cave. This causes additional infrastructure costs for bending magnets and concrete shielding. The output temperature and pressure of the existing liquefier seems to fit directly to the method of thermosyphon cooling with two phase He.

8.4 Liquid He Consumption

The He consumption of the system should not exceed a value corresponding to about 40 W cooling power for cooling the coils (liquid He at 4.4K). In addition, the cooling of the current leads should not exceed a value of 0.7 g/s liquid He returned at room temperature. These numbers assume that single phase liquid He will be used for cooling of the coils. The expected liquid He consumption of the system, in particular the input as well as the return temperatures, pressures and flow rates should be specified separately for the main components (current leads, coils, coil support, interconnection lines, local dewar). In 2 phase regimes the liquid content by mass must be given.

The limits specified above should not be exceeded after 6 month of continuous operation.

8.5 Liquid Nitrogen Consumption

The liquid nitrogen consumption should not exceed a value corresponding to 300 W cooling power at 80 K. This limit should not be exceeded after several month of continuous operation. Two phase liquid Nitrogen should be used for cooling the radiation shield. The preferred pressure of the LN_2 supply to be provided by GSI is 4.5 bar.

8.6 Cryogenic Interface

The refrigerator is not part of the magnet system. The existing refrigerator needs to be modified to provide liquid He at the pressure necessary to operate the system with single phase He. It could provide for example He at 10 bar pressure and 5.9 K and accept the returned He at 1.2 bar, 4.4 K. The system converting this input pressure and temperature to the values required by the magnet (c.f. Figure 16) should be part of the magnet system. The connection lines between the refrigerator and the cryogenic interface of the magnet (maximum length 10m) are excluded from the system. However, an additional offer can be made for the delivery of the connection lines with a separate cost estimate. Since the exact location of the refrigerator is not yet determined, only crude estimates are expected for the latter. They should be based on a distance of 10m between refrigerator and magnet assuming 4-6 elbows. The maximum height of the external cryogenic system must stay below 10.5 m. The anticipated mid-height of the existing 1000 l dewar amounts to app. 8 m.

The main liquid Nitrogen dewar and the connection lines from the dewar to the magnet are not part of the magnet system and will be installed by GSI. Any additional liquid Nitrogen dewar needed directly at the magnet is considered part of the cryogenic interface which belongs to the magnet system.

The exact location and type of interface (flanges) between the magnet and the connection lines for liquid He should be determined by the vendor in agreement with GSI during the phase of a detailed technical design.

8.7 Quench Behavior

The design of the coils must guaranty that the peak temperature produced in the conductor during a quench at full field does not exceed ~100 K with all the magnetic energy dissipated in the coil system. The option of using an external resistor for the dissipation of field energy should be foreseen. In the latter case the voltage produced at the coil terminals during a quench must not exceed 200 V. All test voltages must be at least a factor of two higher than the expected operating voltage under all conditions.

9 Vacuum System

A leak test of the cryostat should be performed. The total leakage rate should stay below $2*10^{-7}$ mbar l/s. The residual gas pressure of the cold system with the turbopump disconnected should not exceed $5*10^{-7}$ mbar.

The turbopump for the vacuum system will be provided by GSI together with the high vacuum valve. Only a flange on the main support ring is included in the toroid system. The flange should be mounted sideways on the main support ring pointing upstream. A CONFLAT flange with 150 mm diameter (CF 150) is most suitable for that purpose. The turbopump will be placed on a separate support.

The system should be equipped with adsorption elements, such that the turbopump can be switched off once the system is cold.

The vacuum gauges should be connected to the cryostat via CONFLAT flanges with 35 mm inner diameter (NW 35 CF) in order to fit to the common GSI system. The vacuum gauges should be compatible to the GSI vacuum-control system. GSI can provide all vacuum gauges in accordance with the requirements to be defined during the phase of the detailed technical design.

10 Control and Monitoring System

A control and monitoring system should be delivered as a stand-alone system together with the magnet. It should include:

I. Vacuum monitoring,

II. magnetic field monitoring,

III. temperature monitoring and control,

IV. Quench control.

The magnet system excludes vacuum pump, power supply and refrigerator system. It is assumed, however, that the control and monitoring system of the magnet provides an interface to the refrigerator power supply and to the pump. The latter could consist in the simplest case of a vacuum flange for vacuum gauges provided by GSI (cf. section 9). The power supply and the refrigerator interfaces will be modified according to the specification of the control and monitoring system of the magnet. The offer should contain a description of the anticipated interfaces to the power supply, refrigerator and vacuum pump.

Further, an interface to the common HADES control and monitoring system should be provided. A slow data transfer (e.g. 9600 Baud) based on a common, commercially available interface is sufficient. This

interface should not be used to adjust parameters of the magnet system but serves solely monitoring purposes.

11 Safety Requirements

The safety requirements are determined by the usual constraints defined by the German TÜV: The liquid Helium as well as the liquid Nitrogen pipe should be connected to safety valves which open at the moment the pressure exceeds a limit which is defined by the pressure at which the pipes were tested. In addition, the vacuum case should be connected to a safety valve which opens at the moment the pressure inside the cryostat exceeds atmospheric pressure. The system needs approval by the German TÜV. If the safety requirements of the TÜV are taken into account, it is sufficient to get approval on the basis of detailed drawings of the vacuum case of the cryostat. It is the duty of the supplier to take care that the requirements of the German TÜV are fulfilled and, in particular, to provide all documents needed for TÜV approval.

12 Summary of the Torus properties

The following table lists the main properties of the HADES toroid:

Geometry, Field	
No of coils	6
Current	485000 A turns
mean Current Density of the Coil	(100-125) A/mm^2
Peak Field	3.55T - 3.75 T
Magnetic-Field Energy	1.4 MJ
Net Force per Coil	4.9 t
Polar Acceptance	18^o - 85^o
Width of Coil Case	80 mm
Cryostat Diameter	ca. 3.7 m
Cryostat Length	ca. 2.2 m
Materials	
Coil	Al stabilized superconductor (Nb Ti in Cu matrix)
Coil Case, Coil Support	Al
backward Support Ring	no constraints,
forward Support Hexagon	Al
Constraints due to existing Equipment	
liquid He Consumption	< 40 W (4.4 K), < 0.7 g/s (300 K)
liquid Nitrogen Consumption	< 300 W at 80 K
Power Supply: Current, Voltage	≤5000 A, < 4 V

Table 5: Main properties of the HADES toroid The limits on the power supply voltage and current do not apply if the power supply is delivered by the vendor.

13 Transportation of the System

13.1 Responsibilities

The vendor is responsible for shipping the system from the company site to GSI. In order to reduce the chance of possible damage during transportation the system must be protected against expectable external mechanical or thermal loads (e.g. vibrations, usual temperature variations). The exact delivery date must be announced at least 1 weeks in advance.

13.2 Geometrical Constraints

The widths of the internal GSI road system stays above 5 m. Its minimum height amounts to 4.5 m. The entrance gate to the experimental area has a height of 4.2 m and a width of 4.5 m (max. 4.7 m). Inside the experimental area a crane is available (20 t) with a usable height of 11.7 m.

13.3 Installation Support by GSI

During the final assembly phase GSI can provide support in terms of workshop capacitance and manpower if announced sufficiently in advance. Two mechanics will be associated full time to the project during the whole installation phase. In addition, workshop capacitance regarding usual milling or drilling machines will be provided. For special installation tasks a larger group of several technicians and mechanics will be available.

14 Contract Duties

14.1 Vendor Duties

The vendor shall submit the documentation listed below. A rough time schedule for these reports should be included in the offer.

I. Project Management Plan

II. Conceptual Engineering Design

III. Quality Assurance Plan

IV. Manufacturing Plan including detailed time schedule

V. Final Engineering Design

VI. Progress Report every 3 month

VII. Results of Tests of the 1st Superconducting Coil

VIII. Results of Test and Commissioning performed at the Company Site

IX. Results of Tests and Commissioning performed at GSI. Magnetic field measurements at a set of reference points at low (10%) and maximum current verifying the geometrical constraints should be included in these tests.

The conceptual as well as the final engineering design need approval by GSI based on a set of appropriate drawings.

Any event which causes a delay of the manufacturing process must be immediately reported to the HADES project engineer at GSI. All Reports will be property of GSI. All tools manufactured for the particular purpose of the production of the HADES toroid will be property of GSI. During manufacturing and the warranty period all tools should be stored at the vendor site. Afterwards they will be transferred to GSI if not explicitly stated otherwise in the contract.

GSI has the right to check the manufacturing process by visiting the manufacturing site within a week after announcement. If components of the system will be manufactured by subcontractors, GSI must be informed in advance of such a contract. GSI will have the power to veto the placing of a substantial contract or sum of contracts (in excess of 10% of the contract price) if any doubts about the capabilities of the subcontractor exist.

14.2 GSI Duties

I. GSI will provide a technical specification containing all constraints and requirements necessary for a conceptual as well as a detailed technical design within the time schedule for these technical design phases.

II. GSI will release the conceptual technical design within 4 weeks and the detailed technical design provided by the vendor within a period of 8 weeks if no major redesigns are necessary. This approval does not affect the responsibility of the supplier for the whole system. Basis of the approval are the constraints defined in the contract, the additional information described in point I of this list and calculations of the mechanical stability using standard formulas and procedures.

III. GSI will treat information about technical details based on not commonly available knowledge confidential.

IV. GSI will immediately inform the vendor about all events which have an impact on any topic of the contract.