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# The Central Region of a Full-Acceptance Detector

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## 1 Introduction

We discuss several options for implementing detectors in the central region of a full acceptance-detector at a hadron collider such as the SSC.

We take as the major goal of the exercise the instrumentation of $\pm 12$ units of pseudo-rapidity $\eta = -\ln \tan \theta/2$ with roughly uniform quality. There should be no large gaps in $\eta$ at the transition between one detector segment and another, and each segment should not cause effects that compromise measurements in other segments.

The last goal may be hard to achieve in practice, particularly because of interactions in the beampipe, which are aggravated by any significant magnetic field inside the beampipe. This has led Bjorken [1] to propound the use of only quadrupole or higher multipole fields, while allowing that a solenoid field might be acceptable in the central region. In this view dipole fields transverse to the beam are to be avoided.

However, the need to provide a return flux for a central solenoid makes it very difficult to combine this field with forward spectrometers without gaps in the rapidity coverage.

Our perspective on this issue is that of $B$ physics, for which the relevant range of $\eta$ is $\sim \pm 6$ at the SSC. Compared to other collider experiments even this range is extremely wide, and we have long debated the issue of providing a large rapidity coverage. Early thinking considered a solenoid plus forward dipoles [2], or forward dipoles only [3]. The difficulties with these concepts led to the scheme of a central dipole plus compensating forward dipoles [4] which we still regard as the best solution for coverage of $\eta$ up to 6.

In this note we review several options:

- A central dipole plus forward compensating dipoles.
- A central solenoid plus forward quadrupoles.
- A central quadrupole.
- No central magnet.

The central-solenoid option may well be viable, and as is it more compatible with the overall goals of a full-acceptance detector, it deserves continued study.

## 2 Central Dipole

A single central dipole magnet is a logical extension of a pair of forward spectrometers each with its own dipole magnet [3]. The most elaborate presentation of the central-dipole option is in the BCD EOI to the SSC [5]. For reference a half-section of the detector of EOI0008 is shown in fig. 1.

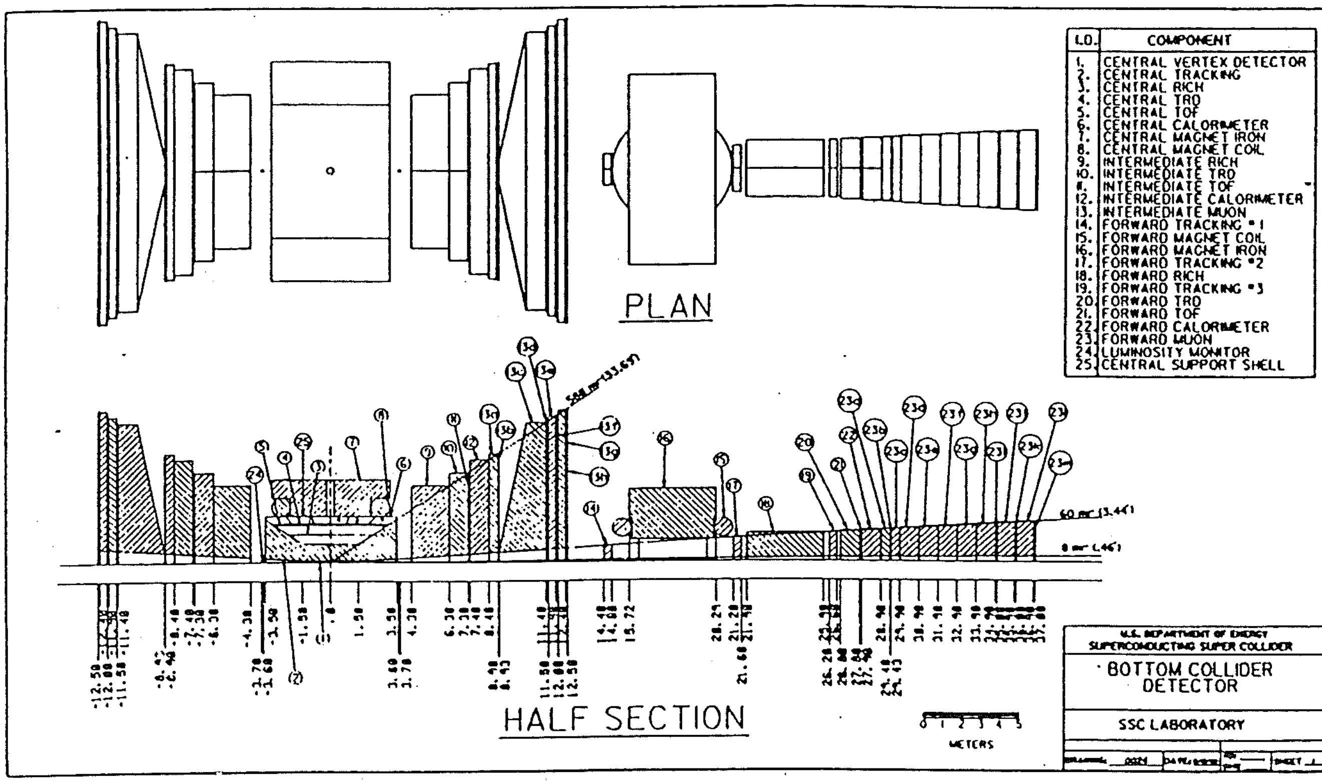


Figure 1: Half section of a detector based on a central dipole and compensating forward dipoles, covering $|\eta| < 5.5$ [5].

A lower-cost detector based on a central dipole is sketched in fig. 2. In this the central region ($|\eta| < 1.2$) is not instrumented initially, and only one forward arm is instrumented for $1.2 < \eta < 5.5$. However, the option is preserved to complete the instrumentation of the central region and the other forward arm with quality similar to that shown.

A brief summary of the detector elements of the forward arm of a compact central-dipole detector with rapidity coverage of $1.2 < \eta < 5.5$ is given below:

1. Central dipole magnet,

   1 T, gap height 4 m, pole tip radius 2 m,

   two small forward dipoles . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . $5M

2. Silicon vertex detector,

   49 disks, 550k channels, $10/channel . . . . . . . . . . . . . . . . . . . . . . . . . . . $5M

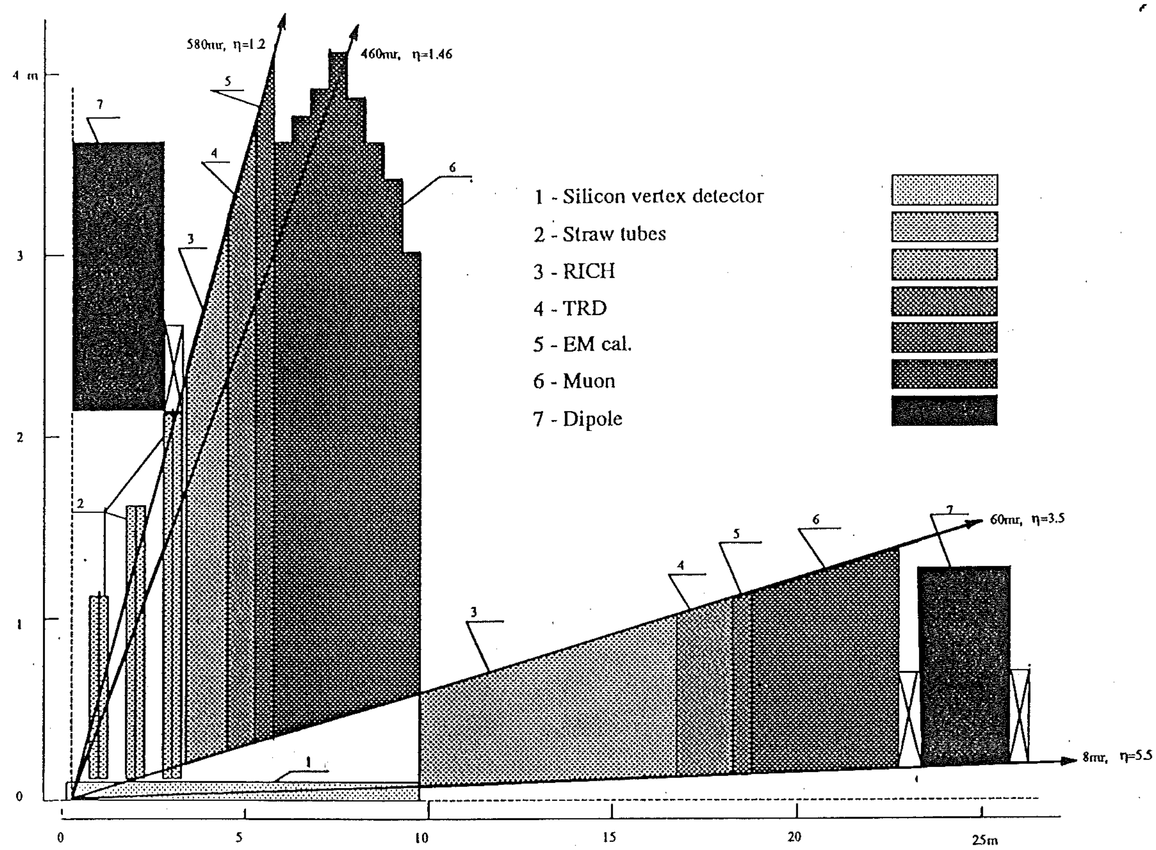


Figure 2: Quarter section of a more compact detector based on a central dipole and compensating forward dipoles, instrumented initially for only $1.2 < \eta < 5.5$.

3. Straw-tube tracking,
   72 planes, 75k straws, $65/straw . . . . . . . . . . . . . . . . . . . . $5M
4. RICH counter,
   60k channels, $40/channel . . . . . . . . . . . . . . . . . . . . $2.5M
5. Transition radiation detector ($\eta < 3.5$ only),
   50k channels, $50/channel . . . . . . . . . . . . . . . . . . . . $2.5M
6. EM calorimeter,
   4k cells, 5 samples/cell, $250/channel . . . . . . . . . . . . . . . . . . . . $5M
7. Muon detector ($\eta > 1.5$ only),
   1800 tons, 12k channels . . . . . . . . . . . . . . . . . . . . $5M
8. Data-acquisition, barrel-switch event builder,
   1000-processor online computer farm . . . . . . . . . . . . . . . . . . . . $10M

9. Contingency.......................................................................$10M

10. **Total**.......................................................................**$50M**

The principal drawback of the dipole-based spectrometer is the beam-pipe problem for $3 < \eta < 5$. We assume the use of a 300-$\mu$m-thick straight pipe, which presents one radiation length for $\eta > 5.3$, and one pion interaction length for $\eta > 6.5$. Already at $\eta = 3$ the pipe appears to be 0.1 radiation lengths thick. As we have noted [6], the transverse dipole fields are rather incompatible with a flared beampipe, as the magnet kicks particles into the flare for a region $\Delta\eta \approx 1$ about the nominal $\eta$ of the flare.

Also, when the central dipole is instrumented to recover the region $|\eta| < 1.2$, there will be a loss of about 15% of the azimuth for $|\eta| < 0.25$ due to particles produced with directions close to that of the magnetic field.

The compensating dipole magnet at 24 m from the intersection point restores the initial angle of any track passing through its aperture. These tracks are offset from their field-free trajectory by 24 m $\times \Delta P_t/P$. The kick $\Delta P_t$ of the central dipole is 0.6 GeV/$c$. Taking 1 GeV/$c$ as the characteristic transverse momentum of tracks of interest, the lowest-momentum track that passes through the 8-mrad aperture of the compensating dipole has $P = 125$ GeV/$c$. In this case the offset of the trajectory due to the dipole pair is 12 cm. A 1-GeV/$c$-$P_t$ track at $\eta = 10$ would suffer an offset of only 1 cm.

While these offsets seem a relatively minor perturbation on the detector quality at $\eta > 5$, it is interesting to consider whether other central configurations might be even more benign.

# 3 Central Solenoid

The extensive success of solenoid-based detectors at colliders makes this a natural option to consider. A uniform solenoid field renders tracking and momentum triggers very straightforward in the central region. The uniform field can only be achieved with massive iron flux returns covering most of the ends of the solenoid, which are somewhat incompatible with the goals of a full-acceptance detector.

Figure 3 sketches a possible implementation of a solenoid plus forward quadrupoles, with the same detector elements as shown in figs. 1 and 2.

Good field uniformity in the solenoid requires the aperture in the end-cap flux return to be restricted to $\eta > 2.5$-3. Fig. 3 illustrates a rather aggressive solution in which the solenoid is 11 m long, with a coil radius of 1.2 m. The central tracking detector would then be about 8 m long. For a solenoid field of 1.5 T, and a tracking resolution of 100 $\mu$m per point, the momentum resolution for a 1-GeV/$c$-$P_t$ track at $\eta = 3$ would still be 1%.

Identification of $\pi^\pm$, $K^\pm$, and $e^\pm$ are all accomplished with RICH counters and scintillator-tile/fiber calorimeters located inside the solenoid flux return for $\eta < 3$. Muons are identified after penetrating the flux return, which is chosen to have a 1-m-thick barrel, and 3-m-thick endcaps (including the steel in the first quadrupole).

The solenoid/quadrupole magnetic-field configuration is compatible with the use of a flared beampipe, as discussed in ref. [6], and we illustrate a pipe with flares at $\eta = 5$ and 6. In an experiment designed to cover only $|\eta| \lesssim 6$ the function of the forward pair of quadrupoles could as well be accomplished by a dipole magnet.

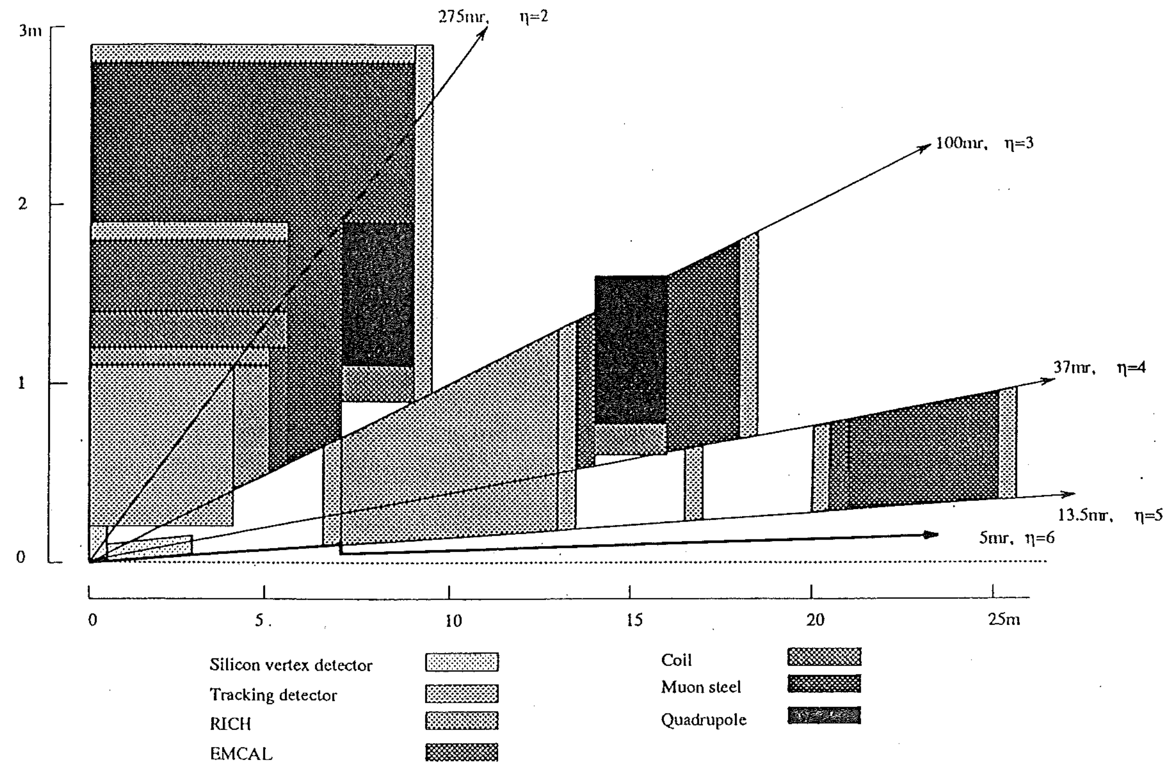


Figure 3: Quarter section of a a detector based on a central solenoid plus forward quadrupoles, shown instrumented for $|\eta| < 5$.

The region $3 < \eta < 5$ is covered with two quadrupole-based spectrometers, each covering one unit of $\eta$. We prefer that the tracking detectors associated with the quadrupoles be outside the quadrupole fields, as shown, so that straight track segments can be found first on each side of a quadrupole. Linking will then be very straightforward.

A single RICH counter could be used to cover $3 < \eta < 5$ as this contains relatively little matter. However, each quadrupole spectrometer must have a separate EM calorimeter and muon identifier.

The silicon vertex detector would be arranged in three segments. For $\eta > 1$ only 'disk' detectors are needed, which are arranged around the conical flare at $\eta = 5$. For $|\eta| < 1$ good vertex determination requires the use of an array of interleaved disks and barrels, which is an ambitious structure.

This detector configuration readily permits staging. For $B$ physics the choice would be whether to implement the solenoid first, or the quadrupole spectrometers. As the quadrupoles only cover 2 units of $\eta$, while the solenoid covers 6 units (or 4 if the end-cap detectors are staged) it seems best to build the solenoid first. This approach may present higher initial costs than the dipole-based detector discussed in the previous section.

# 4 Central Quadrupole

To avoid the need of the flux return that rendered a solenoid magnet difficult in a full-aperture detector, we consider the use of a quadrupole (or higher multipole magnet) in the central region.

For a quadrupole the deflection of a charged particle has a component along the beam, rather than being entirely transverse as for a solenoid. Further, the magnitude of the deflection in a central quadrupole varies with azimuth, and is less than 1/4 of the maximum for 15% of the azimuth. (This loss of useful azimuth holds also for a transverse central dipole, and for any higher multipole magnet as well.)

Tracking must be accomplished with detectors inside the magnetic volume of the central magnet. This is difficult for a central quadrupole on two accounts. First, the trajectories inside a quadrupole are in general curved in any projection (unlike the simple helical trajectories in a solenoid or dipole field) so track fitting would be quite computer intensive, and unsuitable for use in online triggers. The trajectories are most strongly curved at the outer radius of the quadrupole, and relatively straight at small radius. Thus track pattern recognition might logically proceed from inner to outer radii, in distinction to the usual practice. Thus a central quadrupole spectrometer puts a premium on cleanliness of the inner layers of tracking – where present tracking chambers are the weakest.

In a central quadrupole spectrometer the direction of the deflection is sometimes radial or sometimes transverse, depending on the azimuth of the track. In general one desires good spatial resolution along the direction of deflection for good momentum resolution. If one uses tracking detectors such as wire chambers, scintillating fibers, or silicon strip detectors, the wire/fiber/strip orientation would need to be in $x$, $y$, $u$, and $v$ directions, all transverse to the beam. The gaps in such chamber arrays caused by the beampipe and silicon vertex detector are, however, much less annoying in a quadrupole magnet than in a dipole.

The second broad issue is that the strong region of the quadrupole field is only at large radius, so the effective $Bl^2$ of the field is reduced compared to a solenoid or dipole of the same peak field. That is, the momentum resolution attainable with a quadrupole magnet is less than that with a solenoid or dipole, noting that the peak field is set by materials limitations common to all magnets. This effect is somewhat less important for tracks with smaller angles to the beam, for which the kick of the quadrupole improves as noted below.

A related issue is that an electromagnetic calorimeter can be place outside the coil of a solenoid, leaving the full magnetic volume for tracking. However, in a central (superconducting) quadrupole the flux return must lie immediately outside the coil, and any calorimeter placed inside the coil. This greatly increases the magnetic volume, and the peak field at the quadrupole coil, if the same momentum resolution is to be achieved as in a solenoid.

We support the preceding arguments with some simple calculations. For reference, a solenoid of radius $R$ and field $B_S$ causes a sagitta $s$ in the orbit of a charged track of transverse momentum $P_t$ and polar angle $\theta$ of

$$s = \frac{eB_S R^2}{8cP_t} \times \begin{cases} 1 & \text{if track exits side,} \\ \frac{\tan^2\theta}{\tan^2\theta_0} & \text{if track exits end,} \end{cases} \qquad \text{(solenoid),}$$

where $\theta_0$ is the angle from the origin to a point at radius $R$ at the end of the solenoid, and by 'side' we mean the surface at radius $R$. We compare this to a quadrupole of field $B_Q$ at radius $R$, beyond which lie the coils. Here the sagitta for tracks inside the field is

$$s = \frac{\sqrt{3} e B_Q R^2}{27 c P_t} \sqrt{\cos^2 2\phi + \sin^2 2\phi \cos^2\theta} \times \begin{cases} \frac{1}{\sin\theta} & \text{if track exits side,} \\ \frac{\tan^2\theta}{\tan^3\theta_0 \cos\theta} & \text{if track exits end,} \end{cases} \qquad \text{(quadrupole).}$$

In a central quadrupole the sagitta is modulated by the angular factor $\sqrt{\cos^2 2\phi + \sin^2 2\phi \cos^2\theta}$ as there are four directions along which a track emanating from the origin experiences no transverse field. So long as the track exits the side of a solenoid the momentum resolution is unchanged, while in a quadrupole the resolution actually improves as $1/\sin\theta$ for forward tracks. Both solenoids and quadrupoles cause reduced sagitta for forward tracks that exit the end of the field region, but the reduction factor is slightly less for a quadrupole than a solenoid.

To achieve the same sagitta in a field of radius $R$, the fields at that radius obey

$$B_Q = \frac{27}{8\sqrt{3}} B_S \approx 2B_S.$$

While $B_S$ is the field at the coil of a solenoid, $B_Q$ as defined here is only the minimum field at the pole tip of a quadrupole, if conventional construction with iron pole tips is used. To maintain good quadrupole field shape for radii $r < R$ the pole tip should extend out to about $r = (1 + \sqrt{3})R/2 \approx 1.37R$, for which the gap between adjacent poles equals the distance $r - R$ to the desired good field region. Therefore the maximum field in the quadrupole with the same momentum-analyzing power as a solenoid of field $B_S$ is

$$B_{Q,\max} \approx 2.73 B_S, \qquad \text{(conventional quadrupole).}$$

It is also relevant to compare the stored energies in the two magnets. For a solenoid of radius $R$ and length $L$ the stored energy is

$$U_S = \tfrac{1}{8} B_S^2 R^2 L, \qquad \text{(solenoid).}$$

For a conventional quadrupole the majority of the stored energy lies between the pole tips for radii $r > R$. In the approximation that the fields cut off sharply at $r = 1.37R$, we find

$$U_Q \approx 0.59 B_Q^2 R^2 L = 18.7 U_S, \qquad \text{(conventional quadrupole),}$$

where $B_Q = 2B_S$ is the field in the quadrupole at radius $R$ so as to give the same analyzing power as the solenoid.

At the SSC it is more probable that a quadrupole magnet would be of superconducting construction, in which a $\cos 2\phi$ winding on a cylinder of radius $R$ defines the field. In this case the maximum field is just

$$B_Q \approx 2B_S, \qquad \text{(superconducting quadrupole),}$$

and the stored energy is

$$U_Q = \tfrac{1}{16} B_Q^2 R^2 L = 2U_S, \qquad \text{(superconducting quadrupole),}$$

If we include an EM calorimeter inside the central quadrupole, than its inner radius must be about 1.25 that of the solenoid, and so

$$B_Q \approx 2.5 B_S, \qquad \text{(superconducting quadrupole plus EMcal)},$$

and the stored energy is

$$U_Q = \tfrac{1}{16} B_Q^2 (1.25R)^2 L = 4.9 U_S, \qquad \text{(superconducting quadrupole plus EMcal)},$$

In any case the larger peak field, larger stored energy, and azimuthal variation in the magnetic forces of a central quadrupole spectrometer magnet compared to those of a solenoid make the engineering of such a quadrupole more demanding.

For these reasons there may be considerable reluctance to invest in a central quadrupole magnet.

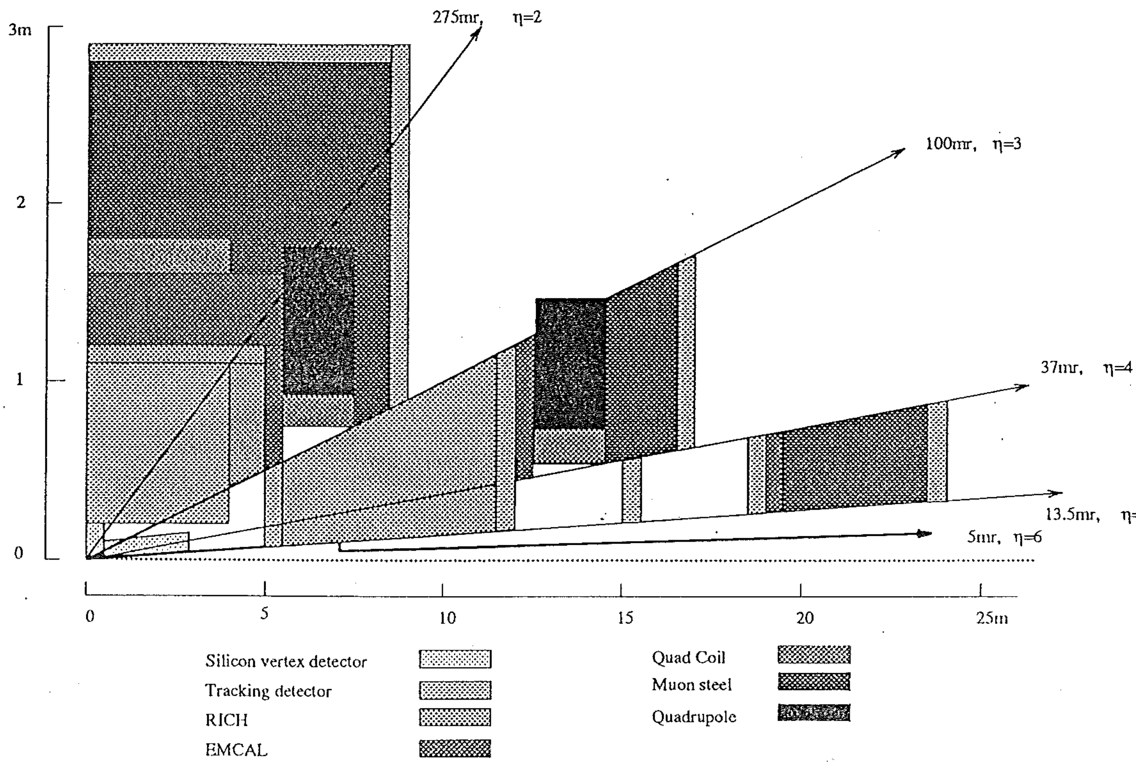


Figure 4: Quarter section of a detector based on a central quadrupole plus forward quadrupoles, shown instrumented for $|\eta| < 5$.

Nonetheless we sketch a possible central detector configuration based on a central quadrupole magnet in fig. 4. The overall concept is closely related to the solenoid-based detector of fig. 3. Because the quadrupole flux return is entirely through the outer radius, the magnet need not be longer than the central tracker, whose corner we again take to be $\eta = 2$. The central EM calorimeter must be inside the (superconducting) quadrupole coil, as there can be no air gap just outside the quadrupole coil where the return flux is very strong. The forward quadrupoles can be moved closer to the intersect, and all forward detector elements made slightly smaller while retaining the same coverage as is fig. 3.

# 5 Field-Free Central Region

One 'solution' to the above difficulties in matching a central magnet to forward ones is to eliminate the central magnet altogether. This approach has been most prominently advocated [7] as a means of simplifying the silicon vertex detector for the forward spectrometer, but is not consistent with the goals of a full-acceptance detector.

Still, one might take the attitude that in the absence of a satisfactory solution to the matching of central and forward detectors, one begins by building only a forward detector, deferring construction of the central detector.

# 6 References


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