STUDY OF AN LHC DETECTOR WITH A CENTRAL SOLENOIDAL FIELD

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A study is made of a selection procedure of parameters of a central solenoidal field of radius R and central field B and a central detector with resolution ε for an LHC detector.

Relevant criteria are:
1) the error on momentum due to resolution and multiple scattering,
2 the synchrotron radiation loss for electrons,
3) the stored energy of the magnetic field,
4) the hoop stress of the coil and the thickness of the support cylinder.

The motion of a particle of momentum p (GeV) and unit charge originating from the point (x,y,z) = (0,0,0) on the axis of the solenoidal uniform magnetic field B (T) is a helix of constant radius of curvature ρ (m) and constant pitch angle λ, while the axis of the helix coincides with the axis if the solenoidal field. I get

$$p \cos \lambda = 0.3\, B\, \rho = \frac{0.3\, B}{k},$$

where k is the curvature of the particle track, and λ is the angle with respect to the plane normal to the z - direction (along the beam) at the point (0,0,0).

Particles originating from the point (0,0,0) on the axis escape from the cylinder, if $2\rho \geq R$. The cutoff occurs at $2\rho = R$, at which

$$p_{Tcut} = 0.15\, BR\,.$$

I introduce a parameter

$$\xi = \frac{p_{Tcut}}{p_T} = \frac{R}{2\rho} = \sin \frac{\alpha}{2}\,.$$

Here, α is the bending of the particle trajectory from the axis to the edge of the field, and the projected track length in the bending plane is

$$L' = \rho\alpha\,.$$

The parameter ξ is used over the range 0 ($p_T = \infty$) to 1 ($p_T = p_{Tcut}$).

The errors δk_{res} and δk_{ms} in the curvature due to the measurement resolution and multiple scattering, respectively, and similarly the errors $\delta\theta_{res}$ and $\delta\theta_{ms}$ in the measurement of the polar angle are conveniently expressed as functions of B, R, ξ (α), ε, and the coil length L_m, using the formalism of R.L. Glückstern (NIM 24 (1963) 381 - 389).

I calculate now the momentum resolution of charged particles and the synchrotron radiation loss of electrons for values of the pseudorapidity η = 0,1,2,3 and 4 for a configuration with B = 4T, R = 1 m, ε = 20 μm, and a track detector with a total thickness of 0.12 radiation length (e.g. for microstrip chambers which are expected to operate well in a high magnetic field, F. Udo). The length of the coil is determined by the pseudorapidity range from 0 to η which is completely covered by a tracking region of radius R = 1 m. Table 1 shows the corresponding values of L_m of η.

Table 1

η	tan (θ/2)	θ	L_m	R	pTcut
		rad	m	m	GeV
				L_m = 4 m	B = 4 T
0	1.0000	1.571	0.00	1.000	0.600
1	0.3679	0.705	2.36	1.000	0.600
2	0.1353	0.269	7.22	0.551	0.331
3	0.0498	0.099	20.2	0.200	0.120
4	0.0183	0.037	54.1	0.073	0.044

A reasonable choice of the useful length is L_m = 4 m for which the range $0 \leq \eta < 1.44$ is entirely contained within the tracking region up to R = 1 m. Table 1 also shows the corresponding values of R and p_{Tcut} as function of η. Fig. 1 shows the resolutions for η = 0, 1, 2, 3, and 4. These parameters yield a resolution dp/p ≈ 0.10 p (TeV) for large p compared with dp/p ≈ 0.33 p (TeV) for a field of 1.63T. For the range $0 \leq \eta \leq 2$ this resolution at B = 4 T is better than that of an electron calorimeter with dE/E = 0.01 + 0.17/√E up to 200 GeV and that of a hadron calorimeter with dE/E = 0.01 + 0.35/√E up to 300 GeV. The relative synchrotron radiation loss -dW/E of electrons in this field is less than the energy resolution of above electron calorimeter up to E = 400 GeV.

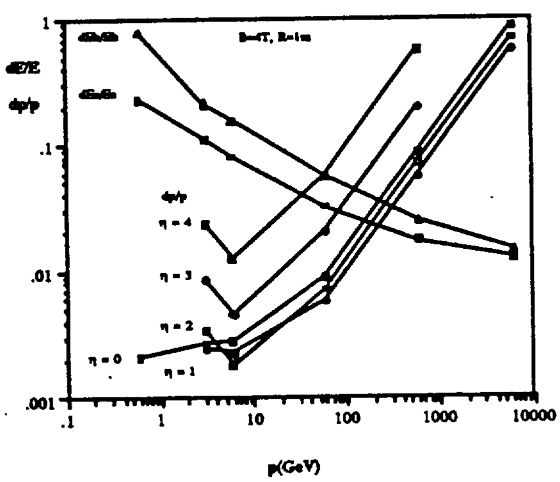

Fig. 1 Momentum resolution for electrons, muons and hadrons for various values of η. The curve dEe/Ee is the energy resolution for an electron calorimeter with dE/E = 0.01 + 0.17/√E. The curve dEh/Eh is the energy resolution for a hadron calorimeter with dE/E = 0.01 + 0.35/√E.

The synchrotron radiation loss for electrons on a trajectory of curvature $\rho(\theta)$ over one revolution is derived below. On a trajectory of curvature $\rho(\theta)$ over one revolution

$$\Delta W_e = -0.0882 \cdot 10^{-3} \frac{\beta^3}{\rho(\theta)} E^4 \text{ GeV} .$$

The radius of curvature is

$$\rho(\theta) = \frac{\rho}{\sin\theta}$$

The relative energy loss over the path length L is

$$\frac{\Delta W_e}{E} = -0.0948 \cdot 10^{-6} \frac{B^3 R'^2}{\sin^2\theta} \frac{\alpha}{\xi^2} .$$

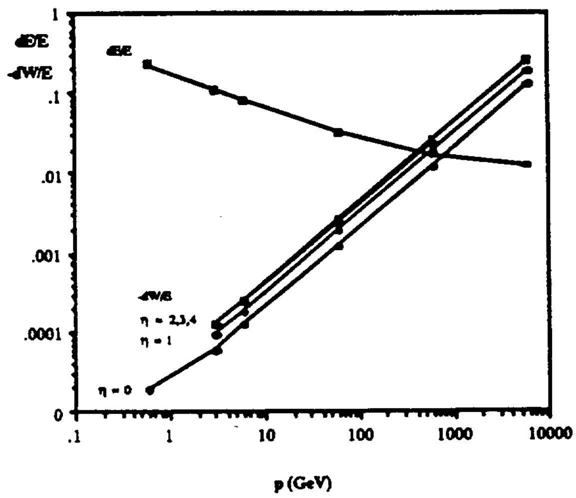

Fig. 2 The synchrotron radiation loss dW/E for electrons in a field of 4 T with a radius of 1 m. The curve dE/E is the energy resolution for an electron calorimeter with dE/E = 0.01 + 0.17/√E.

The stored energy W_s of a magnet with a field of B 4 T, a radius R = 1 m, and a length L_m = 4 m within an iron return yoke is about 104 MJ.

The main limiting factor in the choice of field and radius is the hoop stress described below using Fig.3.The axial field is

$$B\,(T) = \mu_0 nI\,(At/m) = \frac{4\,\pi\, nI\,(At/m)}{10^{-7}} .$$

The Lorentz force per unit length on windings of solenoid is

$$\vec{F} = \vec{I} \times \vec{B} \quad \Rightarrow \quad F\,(N/m) = I\,(A)\,B\,(T) .$$

The radially outward magnetic pressure on n windings per meter

$$P_m\,(Pa) = nI\,B = \frac{B^2}{\mu_0} \approx 0.8 * 10^6\, B\,(T)^2 .$$

The outward pressure on the surface of the cylinder stretches the circumference of the cylinder and causes a hoop stress in the cylinder which is

$$\sigma_2\ (MPa) = P_m \frac{R}{t} \approx 0.8\, \frac{B\,(T)^2 R\,(m)}{t\,(m)} .$$

Existing superconductive solenoids consist e.g. of a cryostat made of Al ($t_{cry} \approx 0.4\, X_0$), the coil (mainly Al stabiliser, $t_{coil} \approx 0.3\, X_0$), and a support cylinder made of Al ($t_{cyl} \approx 0.3\, X_0$). For Al , I have X_0 = 0.089 m, and the allowed hoop stress for Alis $\sigma_{all} \approx 80$ MPa at 293 K, and $\sigma_{all} \approx 120$ MPa at 4.2 K. Only t_{cyl} = 0.0267 m contains the hoop stress.

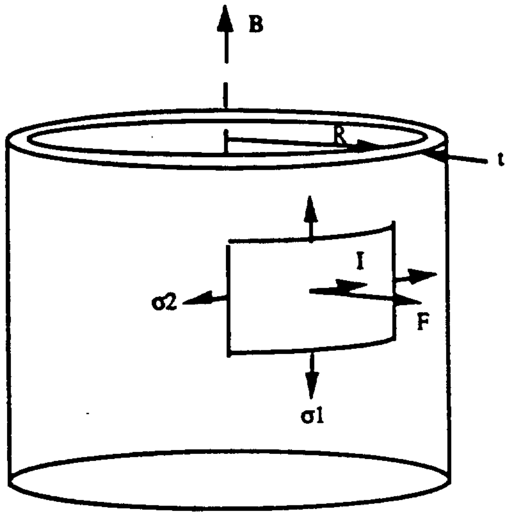

Fig.3. Definition of the hoop stress σ_2.

With $\sigma_2 = 80$ MPa, I get $B^2R = \sigma_2\, t / 0.8 = 80 * 0.0267 / 0.8 = 2.67\ T^2m$, which yields for R = 1 m, B = 1.63 T. E.g. for B = 4T, and R = 1m I need $t_{cyl} = 0.160$ m = 1.8 X_0. Using the same t_{cry} and t_{coil}, $t_{total} = 2.5\ X_0$ which is too large if the coil is followed by a calorimeter. In practice t_{coil} also will depend on B. Existing solenoids are limited to fields of < 1.8 T by the hoop stress in the Al support cylinder

I can design a solenoid with a thin outer support cylinder using for the support cylinder a low Z material of high tensile strength T for which we may take optimistically $\sigma_{all} \approx 0.5$ T for reduction of the total radiation length of the coil and for increasing σ_{all} and thus B for a given radius R. Various materials exist : HT graphite yarn (Z = 6), Boron (Z = 5) fibre with W (Z = 74) core or SiC (Z = 14 and 6) core, Al (Z = 13) Li (Z = 3) alloy (~4:1), Al (Z = 13) and C (Z = 6) fibre composite. For example, using HT1000 graphite yarn (~67 %) in epoxy matrix with T ≈ 7000 MPa and thus σ_{all} = 3500 MPa = σ_2 (from C. Hauviller, CERN), $\rho \approx 1.55$ g cm^{-2}, and $X_0 \approx 0.275$ m I obtain $t_{cyl} \approx 0.05\ X_0 \approx 0.0275$ m, $B^2R = \sigma_2\, t / 0.8 \approx 60\ T^2m$, and for R = 1 m I get B ≈ 7.8 T. This leaves 0.1 - 0.2 X_0 for an Al cylinder, perhaps on the inside of the coil for carrying the He cooling tubes, providing sufficient heat conductivity between He tubes and coil, and quench stability. The thickness of this solenoid would be less than 1 X_0.

The proposed coil design might be used in an Economic Compact Universal LHC detector. A small coil with B = 4 T, R = 1 m and L_m = 4 m is surrounded by an electron and hadron calorimeter which is then situated in a field of up to 0.27 T. The thickness of the coil will depend on the field due to the linear increase of the number of ampereturns with B, and to the decrease of the critical current with B. The calorimeter is surrounded by an iron return yoke instrumented for muon detection. The iron return yoke can have coils for additional excitation, if required for momentum determination of muons (e.g. at large η). The smallness of the coil keeps all other instrumentation Compact and thus such a Universal detector may be relatively Economic.