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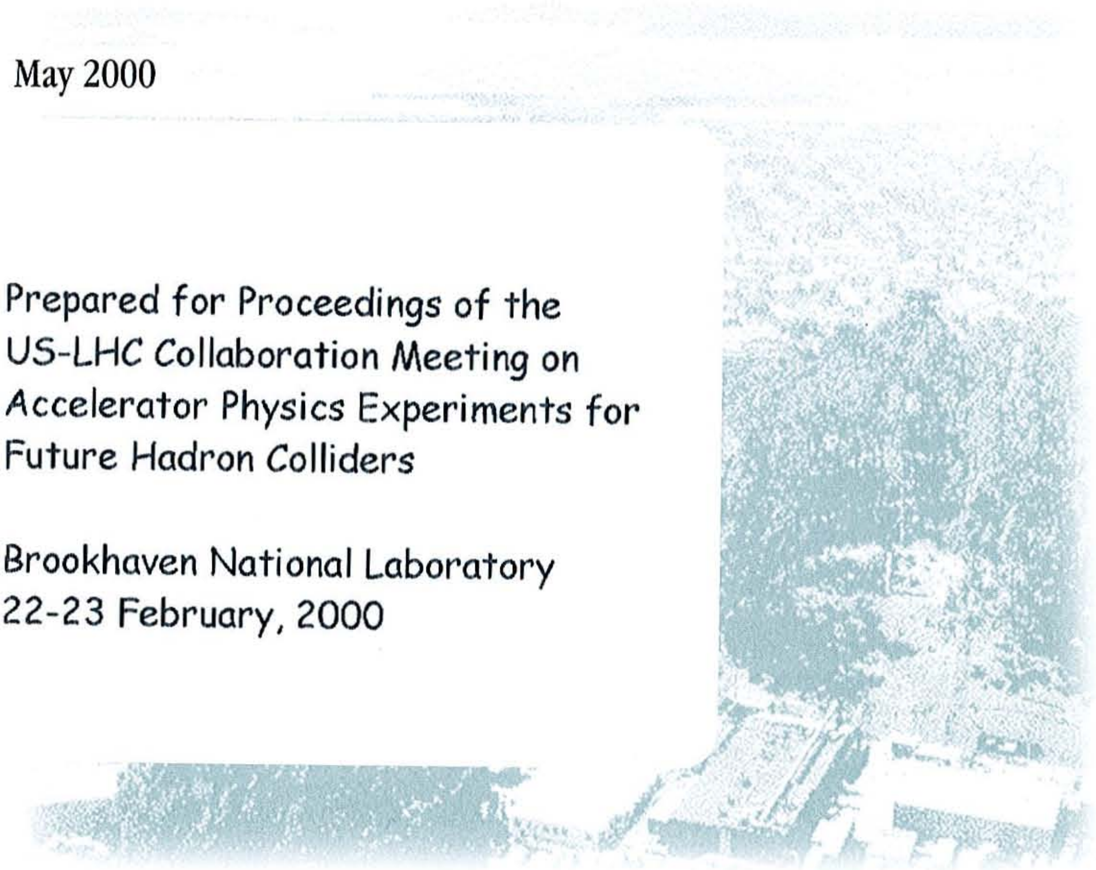
Accelerator and Fusion
Research Division

May 2000



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DISCLAIMER

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Status report on the development of instrumentation for bunch by bunch measurement and optimisation of luminosity in the LHC*

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(12 May 2000)

Abstract

The status of development of instrumentation for bunch by bunch measurement and optimization of luminosity in the LHC is described in this paper. Radiation hard, fast, segmented, gas ionization chambers have been designed for installation near the shower maxima in the IR neutral particle absorbers (TAN) and IR front quadrupole absorbers (TAS). Low noise electronics have been developed to allow measurement over the full range of luminosity ($10^{28} - 10^{34}$ cm^{-2}sec^{-1}) anticipated for the LHC with reasonable integration times. A prototype system will soon be tested with hadronic showers initiated by 450 GeV protons from the SPS.

1 INTRODUCTION

The Large Hadron Collider (LHC) [1] is a 7+7 TeV pp collider being constructed at CERN to operate with very high design luminosity, 10^{34}cm^{-2} sec^{-1}. The high luminosity has many consequences for machine design. The large number of protons per bunch (10^{11}) and the large number of bunches in each ring (2835) are particularly relevant for this paper.

For inelastic cross section 80 mb at 14 TeV cm the forward power of collision products leaving a high luminosity IP in each direction is approximately 1 kW. Absorbers are required to protect IR region superconducting magnets so that less than 1.2 mW/kgm reaches the cold mass. Fig. 1 shows a layout of one half of a high luminosity IR. A front quadrupole absorber (TAS) protects the inner triplet quadrupoles and a neutral particle absorber (TAN) protects the outer beam separation dipole D2.[2] The absorbers are shown filled in black in Fig. 1. Fig. 2 shows contours of power density in the TAN absorber; one sees that the peak power density of the hadronic/electromagnetic showers inside the TAN is in the range 1-10 W/kgm. Table 1 gives the mean number, mean energy and total energy per pp interaction incident on the absorbers. The power density in the TAN is dominated by the showers initiated by neutrons and photons and in the TAS by charged pions and photons. On average about half of the 14 TeV collision energy is deposited in these absorbers. The peak flux of particles of various types at the shower maximum in the TAN is given in Table 2 for design luminosity 10^{34} cm^{-2}sec^{-1}. The cutoff energy for neutrons is .002 eV so the neutron flux includes thermal neutrons. For all other particles the cutoff energy in 0.1 MeV. The flux of neutrons with energy above 0.1 MeV is approximately 2.1×10^{9} cm^{-2}sec^{-1}.

Bunches in LHC are produced in trains with gaps for kicker magnet rise times. Altogether there are 3564 rf buckets spaced 25 nsec apart with nominally 2835 of them filled. A typical bunch structure is 3564 = 12x297 = 11x[3x(81b+8e)+30e]+[2x(81b+8e) +119e] where b denotes a filled bucket and e an empty one. A finite crossing angle ~ 300 μrad is needed to avoid unwanted head on collisions approaching and leaving an IP. Bunches in the middle of a bunch train experience approximately fifteen long range collisions in the common beam tube on each side of an IP. Bunches near the head and tail of a bunch train experience fewer long range collisions (PACMAN bunches). These long range collisions produce orbit distortions and tune shifts in addition to the head on tune shift produced at the IPs.[3] The possibility that bunches experiencing fewer than the nominal number of long range collisions may be unstable has led to the recommendation that the luminosity be measured for each bunch individually.[4]

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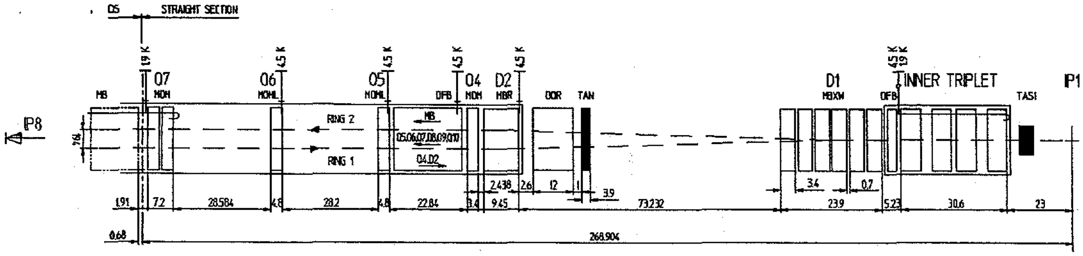

Fig. 1: Layout of one half of a high luminosity insertion IP1(5) of LHC. The front quadrupole absorber (TAS) and the neutral particle absorber (TAN) are shown filled in black.

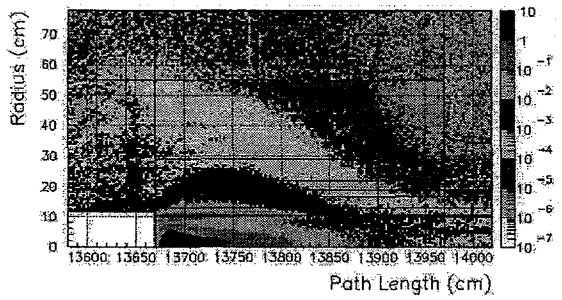

Fig.2: Contours of power density (W/kgm) deposited in the TAN at design luminosity 10^{34} cm^{-2} sec^{-1}.

Table 1: The mean number, mean energy and total energy per pp interaction incident on the (a) TAN and (b) TAS absorbers at design luminosity 10^{34} cm^{-2}sec^{-1}.

(a) TAN

Particle type	<n>	<E> (GeV)	<n><E> (GeV)
Neutral hadrons	.33	2185.	725
Protons	.06	1215.	73
Charged Pions	.71	125.	88
Photons	151	5.	736
Electron/ positron	12.5	1.	8
Muons	.01	25	.25

(b) TAS

Particle type	<n>	<E> (GeV)	<n><E> (GeV)
Neutral hadrons	.58	261.	152
Protons	.29	292.	83
Charged Pions	6.8	159.	1081
Photons	8.3	87.	725
Muons	.06	33	.2

Table 2: The peak flux of particles of various types at the shower maximum in the TAN at design luminosity 10^{34} cm^{-2}sec^{-1}.

Particle type	Flux(cm^{-2}sec^{-1})
Charged hadrons	4.7×10^{8}
Electron/positron	7.5×10^{10}
Photons	1.1×10^{12}
Neutrons	4.6×10^{9}

The existence of the TAN and TAS absorbers led to the proposal to instrument them to sample the power deposited by the hadronic/electromagnetic showers and to use this information as a machine tool to keep the LHC operating near optimum luminosity.[5] Scanning the position of one beam at the IP allows measurement of beam-beam separation and transverse beam size. By segmenting the detectors it may also be possible to measure crossing angle and transverse IP position. The particular situation in LHC leads to a different approach than has been used in storage rings in the past for the measurement of luminosity. The very high power density in the absorbers requires strict attention to radiation hardness; there is no possibility of using glass, plastic, fiber optics, PMTs and organic gasses in this environment. Solid state detectors are probably also ruled out. Furthermore the equipment will become highly activated and if necessary to service would require remote handling. A premium is therefore placed on high reliability and maintenance free operation – hopefully for many years. Since there are approximately 20 interactions per bunch crossing at 10^{34} cm^{-2} sec^{-1} and the multiplicity of particles hitting the absorbers is high there is no possibility of measuring individual events or using coincidence. The detector envisioned therefore measures the locally deposited energy density and relies on cross calibration with a particle detector for absolute luminosity. Single beam backgrounds could cause difficulty with this approach however preliminary estimates indicate they will be quite small.[5] At very low luminosity with less than one pp interaction per bunch crossing, coincidence of detectors on opposite sides of the IP could be used to suppress single beam background.

2 REQUIREMENTS FOR LUMINOSITY MEASUREMENT IN LHC

The requirements of an LHC luminosity monitor for machine operations purposes were established at a mini workshop held at CERN on 15-16 Apr. 1999. They are summarized here.[6]

- Capability of keeping the storage ring tuned within 2% of optimum luminosity
- Correlation of apparent luminosity with position of IP < 1% per mm
- Correlation of apparent luminosity with half crossing angle < 1% per 10 μrad
- Dynamic luminosity range 10^{28} to 10^{34} $\mathrm{cm}^{-2}\ \mathrm{sec}^{-1}$ with "reasonable" integration time
- Bandwidth 40 MHz to resolve luminosity of individual bunches
- Backgrounds less than 10% and correctable
- Cross calibrate with absolute luminosity measurement every few months.

It is important for optimisation of luminosity that the measurement of an apparent change of luminosity not be due to the variation of other beam parameters, such as position of the IP or crossing angle, while the luminosity itself is unchanged. For this reason the correlation of apparent luminosity with IP position and crossing angle are specified to be small; 1% per mm and 1% per 10 μrad respectively.

It is planned that the LHC will operate over six orders of magnitude in luminosity. This is needed to accommodate the TOTEM experiment for measurement of forward pp scattering at low luminosity (~ $10^{28}\mathrm{cm}^{-2}\ \mathrm{sec}^{-1}$) and the high p_T experiments ATLAS and CMS at high luminosity (~$10^{34}\mathrm{cm}^{-2}\mathrm{sec}^{-1}$). A luminosity optimisation tool needs to perform well over the entire range of luminosity.

For the reasons discussed in Sec. 1, it is desirable to measure the luminosity of each colliding bunch pair with 25 nsec bunch spacing which requires 40 MHz bandwidth for electronics.

3 CONCEPT FOR OPTIMISATION OF LUMINOSITY

A concept for optimisation of luminosity is shown in Fig. 3. The two beam centers are separated at the IP by a transverse displacement D(t) which is the sum of an intentional circular sweep of the center of one beam d(t) and an error e(t). If the magnitudes of the intentional sweep and error displacement are small compared to the rms beam size then to lowest order in the displacements the luminosity is given by

$$L = L_0\left(1-\frac{\varepsilon^2+d^2}{4\sigma_*^2}\right) - L_0\frac{\varepsilon d}{2\sigma_*^2}\cos(\omega t-\varphi)\,. \tag{1}$$

A detector current proportional to the luminosity then has a quasi-static term proportional to the optimum luminosity L_0 and a linear oscillation term. The magnitude of the oscillation is proportional to the product of the magnitudes of the error offset and the intentional displacement divided by twice the rms beam size in one transverse direction. For the general situation the detector current may be written as

$$I(t) = e\alpha\varepsilon_{\det} m\sigma_{inel} L \tag{2}$$

where σ_{inel} is the inelastic cross section, m is the multiplicity of particles per event which fall within the acceptance of the detector, ε_{det} is the detection efficiency and α is the number of charge carriers collected per detected particle. The current is integrated over an interval 0 to T, assumed equal to an integer multiple of, or to be large compared to, $2\pi/\omega$, to obtain the luminosity and error offset

$$L_0 = \frac{\int_0^T I(t)dt}{e\alpha\varepsilon_{\det} m\sigma_{inel} T}$$

$$\vec{\varepsilon} = -\frac{\hat{e}_x\int_0^T \cos(\omega t)I(t)dt + \hat{e}_y\int_0^T \sin(\omega t)I(t)dt}{\left(\frac{d}{4\sigma_*^2}\right)e\alpha\varepsilon_{\det} m\sigma_{inel} T}\,. \tag{3}$$

The measurement of $\vec{\varepsilon}$ can then be fed back to the closed orbit bumpers to reduce it to zero. In practice we imagine that reducing $\vec{\varepsilon}$ to the level of $0.1\sigma_* = 1.6\mu m$ is sufficient. The magnitude of the optimum sweep amplitude d is equal to the desired residual error, in this case $0.1\sigma_*$. Eqns. 3 can be used to derive expressions for the statistical errors of L_0 and $\vec{\varepsilon}$ as functions of the integration time T.[5]

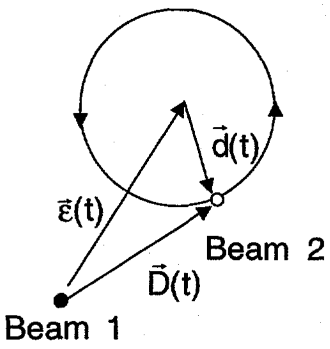

Fig. 3: Concept for optimisation of luminosity; e(t) = error offset of the two beam centers at the IP, d(t) = intentional circular sweep of the transverse position of beam 2.

Preliminary investigations have been made of the possibility that beam sweeping indicated in Fig. 3 could increase the beam emittance. So far the simulations have not observed such a deleterious effect for the bunch intensities envisioned for LHC.[7],[8]

4 IONIZATION CHAMBER PROPERTIES

An illustration of luminosity instrumentation in the TAN and TAS absorbers is shown in Fig. 4. The instrumentation is located near the shower maximum energy density approximately 25 cm behind the front face of the absorbers. The radiation power density in a transverse plane in the TAN is shown in Fig. 5(a). The peak power density is 21 mm from the two beam centerline (symmetry axis of the absorber) owing to the 150 μrad half crossing angle. The beam tube on the left in Fig. 5(a) is enlarged compared to the one on the right to allow synchrotron light from the outer beam separation dipole to pass through the TAN to a synchrotron radiation monitor. Since this simulation was made, the location of the synchrotron monitor has been moved to the other side of the separation dipole so the left beam tube is now circular and symmetrically placed relative to the right beam tube. The instrumentation shown in Fig. 4 has been segmented into quadrants to allow measurement of the crossing angle and the transverse position of the IP by measuring the left – right and up – down asymmetry ratios. The sensitivity of the left – right asymmetry ratio as a function of the position of the center of the power profile is shown in Fig. 5(b).

A survey of possible detectors led to the choice of a gas ionization chamber based on considerations of radiation hardness, reliability and low maintenance and simplicity of installation.[9] The key problems to solve with this approach are bandwidth, acceptable signal to noise ratio and impedance matching to the front end electronics. The solution to these problems led to a multi-plate pressurized ionization chamber. The operating gas would be 4 atmospheres of $Ar+1\%N_2$. Some parameters of the ionization chamber are given in

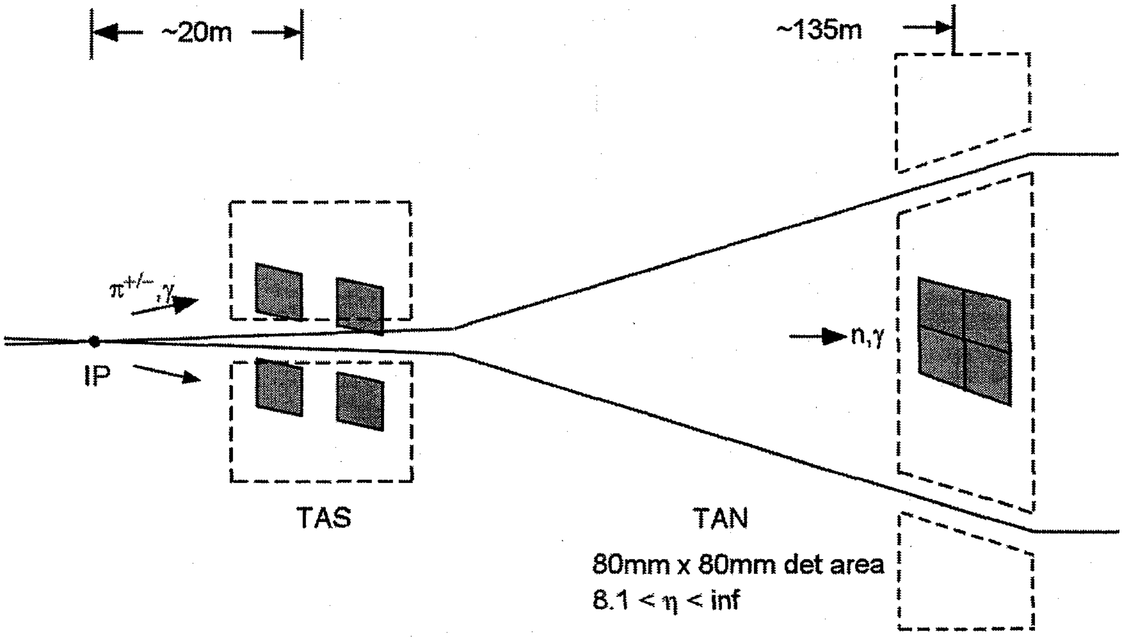

Fig. 4: Illustration of ionization chamber detectors in the TAN and TAS absorbers.

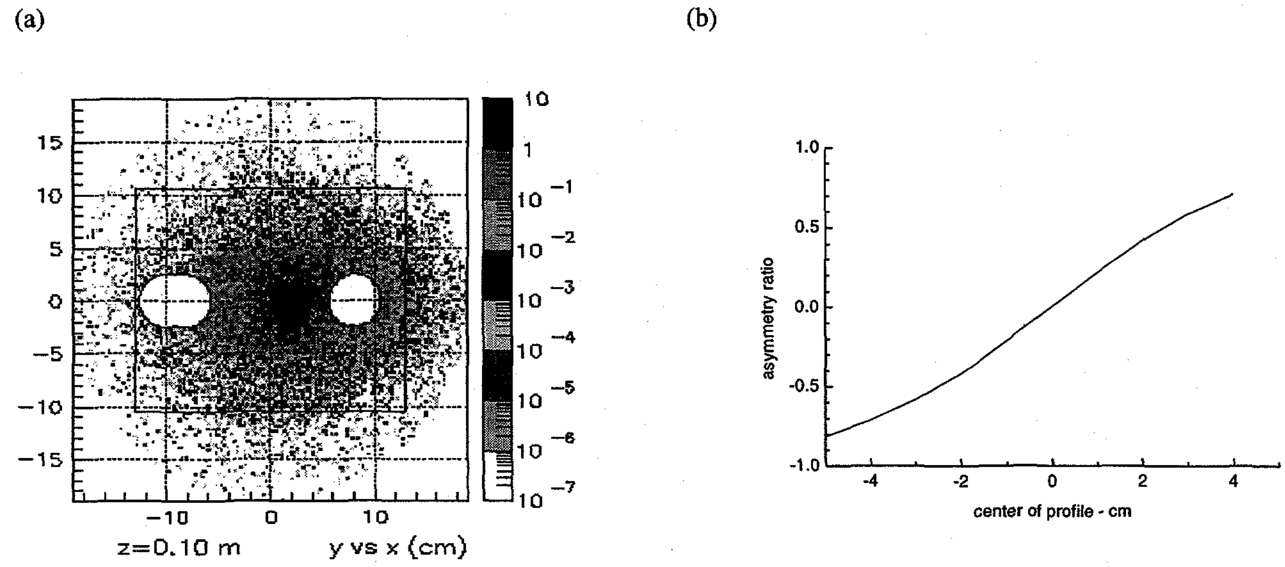

Fig. 5: (a) Contours of radiation power density (W/kgm) in the transverse plane deposited in the TAN at design luminosity 10^{34} cm^{-2} sec^{-1} and (b) left – right asymmetry ratio as a function of the center of the radiation power density profile.

Table 3: Properties of the ionization chamber.

Property	Value	
Active Area (1 quadrant)	40mm x 40mm	
Plate gap	0.5mm	
No. of gaps	60(electrically 10 parallel x 6 series)	
Capacitance per gap	28.3pF	
Gas	Ar+1%N_2, 4x760 Torr	
Gap voltage	150V	
Electron gap transit time	21.7nsec	
Bunch freq/Rev freq	40.079MHz/11.2455kHz	
Bunch structure	12x(3x81+2x8+38)=3564	
Inel pp int/bunch xing @ 10^{34}cm^{-2}sec^{-1}	20	
mip per pp int	268	
mip per bunch xing @ 10^{34}cm^{-2}sec^{-1}	5.35x10^3	
Electron-ion pairs/cm-mip	388	
Ioniz e^-/pp int	5.2x10^3 (1 gap)	5.2x10^4 (10 gaps)
Ioniz e-/bunch xing @ 10^{34}cm^{-2}sec^{-1}	1.04x10^5 (1 gap)	1.04x10^6 (10 gaps)

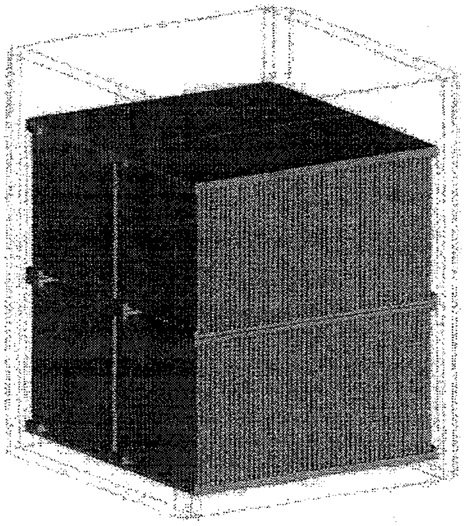

Fig. 6: Illustration of the multi-plate ionization chamber.

Table 3. The gap width 0.5 mm is chosen so the electrons clear the chamber between 25 nsec bunch crossings. The number of gaps and their series-parallel electrical configuration is chosen to match the ionization chamber capacitance plus cable impedance rise time to the front-end amplifier peaking time (2 nsec) and to achieve signal to noise ratio ~ 8:1 for 1 pp interaction ($5 \times 10^3 e^-$ per gap on average). Our solution to these conditions leads to sixty 0.5 mm gaps arranged in six series groups of ten gaps in parallel. An illustration of the multi-plate, segmented ionization chamber is shown in Fig. 6.

Our solution to the problem of measuring luminosity over six orders of magnitude has been to design a detector and electronics package that can detect a single pp interaction in the LHC. In a single pp interaction on average 5.2×10^3 electron-ion pairs are produced per gap. The pre-amplifier and pulse shaper has been designed to produce a 35 mV signal from the induced electron charge collected from ten gaps in parallel ($1/2 \times 10 \times 5.2 \times 10^3 e = 2.6 \times 10^4 e$). With an equivalent noise charge (ENC) less than $3 \times 10^3 e$, the signal to noise ratio is ~ 8.7. Under these circumstances luminosity can be measured to arbitrarily low values, until the single beam background limit is reached, by simply counting ones and zeros as bunches cross. This is the traditional pre LHC era situation. The single beam background limit estimated for beam gas interactions corresponds to luminosity ~ 10^{26} cm^{-2}sec^{-1}, two orders of magnitude below the luminosity expected for TOTEM operation.[5]

In the very low luminosity limit, with a small probability of a pp interaction per bunch crossing, the single beam background could be further reduced by operating the ionization chambers on opposite sides of the IP in coincidence. At ultimate luminosity, 2.5×10^{34} cm^{-2} sec^{-1}, the average number of pp interactions per bunch crossing is fifty. The average induced charge collected from ten parallel gaps is $50 \times 2.6 \times 10^4 e = 1.3 \times 10^6 e$ and the pre-amplifier pulse shaper output voltage is 1.25 Volts.

The ion drift velocity is much less than for electrons so that in equilibrium an ion space charge distribution corresponding to 1.5×10^3 bunch crossings builds up in the gaps. Even at ultimate luminosity 2.5×10^{34} cm^{-2} sec^{-1} this ion space charge has been calculated to be well below the level where recombination is significant; the ionization chamber signal remains a linear function of luminosity.[5]

5 INTEGRATION TIME

Estimates of the integration times for measurement of luminosity, beam-beam separation, crossing angle and transverse position of the IP are given in Table 4 for luminosities 10^{34} and 10^{28} cm^{-2}sec^{-1}. The estimates are conservative since they include the statistics of only the hadrons in Table 1. The number of bunches in each proton beam is assumed to be 2835 for 10^{34} cm^{-2}sec^{-1} and 36 for 10^{28} cm^{-2}sec^{-1}. The rms precision of each measurement is indicated in the first row; for example $\sigma_L/L = .01$. The integration times are given in three units; seconds, turns and bunch crossings. The integration times in Table 3 refer to measurements of the means averaged over all bunches. For measurements of individual bunches to the stated precision the integration times in Table 4 need to be multiplied by the number of bunches. Even for the low luminosity 10^{28} cm^{-2}sec^{-1} the integration times are sufficiently short to be practical; for example approximately one minute for a 1% measurement of luminosity averaged over the 36 bunches and approximately a half hour for 1% measurement of luminosity of each bunch. At 10^{34} cm^{-2}sec^{-1} the integration time for 1% measurement of luminosity averaged over all bunches is one turn and the time to measure beam-beam separation to $0.1\sigma^*$ is 11 turns.

6 STATUS OF DEVELOPMENT

As of the writing of this paper a prototype ionization chamber has been designed and is in fabrication. Prototype pre-amplifiers and pulse shaping boards have been bench tested and meet the bandwidth (40 MHz) and noise requirements (ENC < $3 \times 10^3 e$). In the Summer of 2000 a one week beam test is scheduled in the H4

Table 4: Integration times for measurement of luminosity, beam-beam separation, crossing angle and transverse position of the IP.

Integration time (sec/turns/bunch crossings)				
L ($cm^{-2}sec^{-1}$)	$\frac{\sigma_L}{L} = 0.01$	$\sigma_\varepsilon = 0.1\sigma^*$	$\sigma_\psi = 1\,\mu rad$	$\sigma_{a^*x} = \sigma^*$
10^{34}	6.2x10^{-5} 0.7/ 2.0x10^{3}	1.0x10^{-3} 11/ 3.1x10^{4}	2.55x10^{-4}/ 2.9/ 8.2x10^{3}	3.8x10^{-3}/ 42.6/ 1.2x10^{5}
10^{28}	62/ 7.0x10^{5}/ 2.5x10^{7}	1.0x10^{3}/ 1.1x10^{7}/ 4.0x10^{8}	2.55x10^{2}/ 2.9x10^{6}/ 1.0x10^{8}	3.8x10^{3}/ 4.3$10^{7}$/ 1.5x10^{9}

beamline of the SPS at CERN. The prototype four quadrant ionization chamber will be mounted behind a steel absorber. A slow spill of 450 GeV protons will be incident on the steel absorber; ~ 10^6 p per 2.4 sec spill, repeated every 14.4 sec. The ionization chamber will be set up behind the steel absorber to measure the flux of ionizing shower particles. The pulses of electron charge and the ion current reaching the plates will be measured separately by fast and slow electronic circuits. Provisions are made for varying the thickness and A/Z of the absorber plates, the gas pressure and composition and the transverse position of the chamber in the showers. In the future it is planned to continue these measurements with a 25 nsec bunched beam. The experimental set-up is being modelled with the MARS radiation code to allow comparison of the measurements with expectations.[11]

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