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CLOUD: AN ATMOSPHERIC RESEARCH FACILITY AT CERN

B. Fastrup, E. Pedersen

University of Aarhus, Institute of Physics and Astronomy, Aarhus, Denmark

E. Lillestol

University of Bergen, Institute of Physics, Bergen, Norway

M. Bosteels, A. Gonidec, J. Kirkby*, S. Mele, P. Minginette, B. Nicquevert, D. Schinzel, W. Seidl
CERN, Geneva, Switzerland

P. Grundsøe, N. Marsh, J. Polny, H. Svensmark

Danish Space Research Institute, Copenhagen, Denmark

Y. Viisanen

Finnish Meteorological Institute, Helsinki, Finland

K. Kurvinen, R. Orava

University of Helsinki, Institute of Physics, Helsinki, Finland

K. Hämeri, M. Kulmala, L. Laakso, C.D. O'Dowd

University of Helsinki, Lab. of Aerosol and Environmental Physics, Helsinki, Finland

V. Afrosimov, A. Basalaev, M. Panov

Ioffe Physical Technical Institute, Dept. of Fusion Technology, St. Petersburg, Russia

A. Laaksonen, J. Joutsensaari

University of Kuopio, Department of Applied Physics, Kuopio, Finland

V. Ermakov, V. Makhmutov, O. Maksimov, P. Pokrevsky, Y. Stozhkov, N. Svirzhevsky
Lebedev Physical Institute, Solar and Cosmic Ray Research Laboratory, Moscow, Russia

K. Carslaw, Y. Yin

University of Leeds, School of the Environment, Leeds, United Kingdom

T. Trautmann

University of Mainz, Institute for Atmospheric Physics, Mainz, Germany

F. Arnold, K.-H. Wohlfrom

Max-Planck Institute for Nuclear Physics (MPIK), Atmospheric Physics Division, Heidelberg, Germany

D. Hagen, J. Schmitt, P. Whitefield

University of Missouri-Rolla, Cloud and Aerosol Sciences Laboratory, Rolla, USA

K.L. Aplin, R.G. Harrison

University of Reading, Department of Meteorology, Reading, United Kingdom

R. Bingham, F. Close, C. Gibbins, A. Irving, B. Kellett, M. Lockwood

Rutherford Appleton Laboratory, Space Science & Particle Physics Depts., Chilton, United Kingdom

J.M. Mäkelä

Tampere University of Technology, Department of Physics, Tampere, Finland

D. Petersen, W.W. Szymanski, P.E. Wagner, A. Vrtala

University of Vienna, Institute for Experimental Physics, Vienna, Austria

CLOUD[†] Collaboration

*) spokesperson

†) Cosmics Leaving Outdoor Droplets

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1 Introduction

1.1 Overview

At its meeting on 6 September 2000, the SPSC suggested that CLOUD [1, 2] should be considered as a facility rather than a single experiment. We welcome this suggestion, which corresponds with earlier informal discussions that we had with CERN management. This document therefore places CLOUD in the framework of a CERN facility for atmospheric research. It also addresses some questions raised by the SPSC at the same meeting, concerning the use of a CERN PS beam.

1.2 An Atmospheric Research Facility at CERN

Clouds are the familiar but complex engines of the world's weather and climate. Basic questions remain unanswered about the physicochemical production of the aerosols on which the water droplets or ice crystals form. Under certain conditions, ionisation of the air by cosmic rays may play a vital part. Theoretical studies and direct observations of ion effects from aircraft and balloons give important clues, but adequate laboratory facilities to investigate the microphysics under controlled conditions on the ground do not yet exist.

The experimental concept of CLOUD begins with studies of the various microphysical processes by which cosmic rays may affect cloud formation in the atmosphere. The initial programme contains five groups of experiments dealing with (1) nucleation and growth of aerosols, (2) formation of cloud droplets, (3) production of condensable vapours, (4) creation of ice nuclei, and (5) dynamics of stratospheric clouds. This programme is only indicative, and the actual investigations will respond to our experimental results and associated theoretical developments.

For performing the CLOUD investigations we propose (Figs.1 and 2) to combine a novel expansion cloud chamber with a reactor chamber and associated experimental systems for gas and particle analysis. Reasons for designating CLOUD as CERN's Atmospheric Research Facility are as follows:

- The concept of a facility is appropriate for the comparatively large and complex experimental programme of CLOUD.
- CLOUD is a 'general purpose' detector. Flexibility is required because we do not know what we shall discover or where rapid experimental and theoretical developments may lead us.
- No such facility is presently available to atmospheric scientists at any other location worldwide.
- A time span for the experiments of several years is envisaged.
- Our team already includes atmospheric scientists from 10 institutes in 5 countries but we can expect others to propose experiments when they know of the existence of the facility and its unrivalled capabilities.

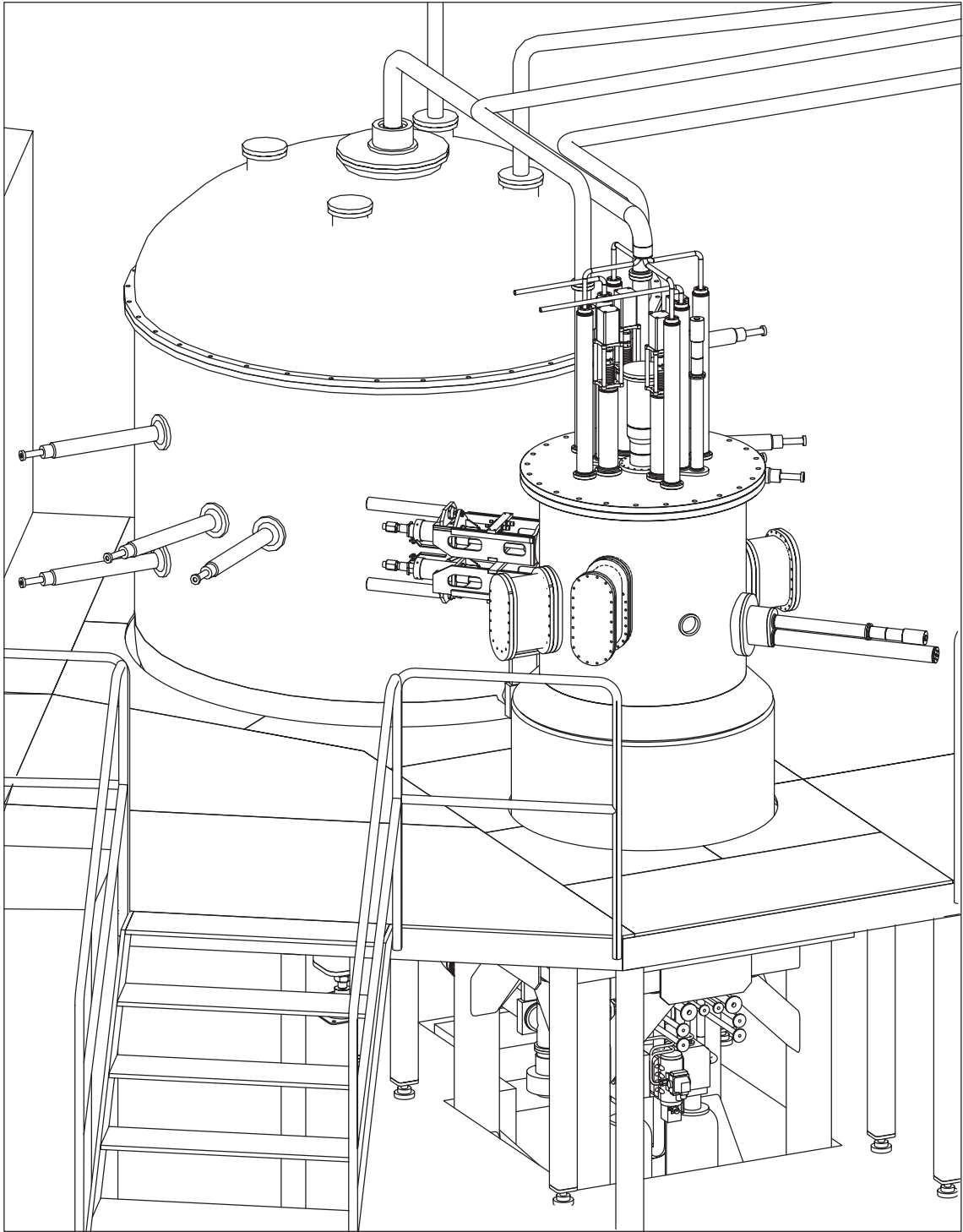


Figure 1: Perspective view of the proposed CERN Atmospheric Research Facility, CLOUD.

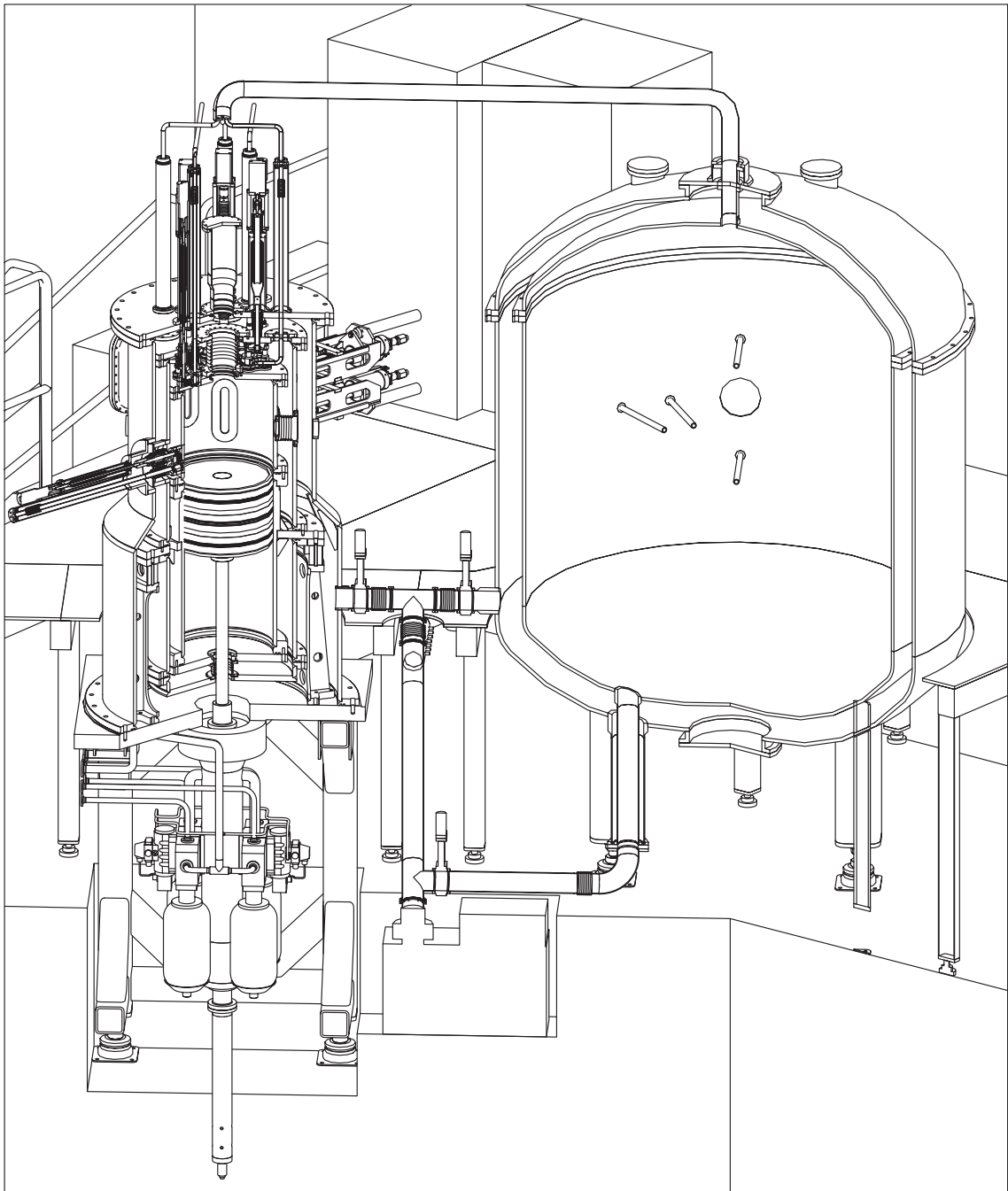


Figure 2: Cut-away view of CLOUD.

Why at CERN? We consider the use of a CERN particle beam to be crucial. Carefully-controlled and precisely-delivered particle ionisation at natural GCR intensities and ionisation densities (corresponding to minimum ionising particles) is a central part of this experiment. Experiments by members of our collaboration and others have obtained useful results with traditional sources of ionisation such as X rays and radioactive sources. But to make further progress requires a beam from a particle accelerator. Only a particle beam can closely duplicate the characteristics of cosmic rays throughout the atmosphere and deliver a precisely known ionisation with the flexibility of intensity, timing, spatial distribution and penetration range that the facility requires.

In addition, CLOUD relies heavily on CERN’s expertise with bubble-chambers and cryogenic temperature control (required to within 0.01K stability). We also need assistance from CERN for the technical integration of what we consider to be a large and complex experiment, as well as for computing support.

It is this combination of a particle beam and specialised technical expertise that makes CERN uniquely suitable for the proposed facility. In a broader context, the creation of the Atmospheric Research Facility will give very positive signals (1) that particle physics has direct relevance to terrestrial concerns, and (2) that CERN welcomes cross-disciplinary research proposed by scientists in its member states who are not particle physicists.

2 Particle beam

2.1 Beam requirements

The primary task of CLOUD is to investigate how galactic cosmic rays (GCRs) may influence cloud formation. To do this we plan to establish realistic atmospheric conditions inside a cloud chamber and reactor chamber, and irradiate the chambers with a particle beam to provide a realistic and adjustable source of “cosmic rays”. We can estimate the beam intensities required for CLOUD as follows.

The desired beam intensity is between $1\times$ and about $10\times$ the natural GCR flux at a given altitude. This will allow us to measure the dependence of any observed effects on ionisation rate and ion pair concentration, and to extrapolate reliably across the range of natural ionisation in the atmosphere. The highest beam intensities will help to amplify and expose effects before they are measured at natural ionisation levels. Beam-off data will be also be recorded, under conditions with the chamber clearing fields on and off, respectively, corresponding to $0.01\times$ and $1\times$ the natural GCR ion pair concentrations at ground level. The optimum operating energy of the proposed T11 beam is near the maximum (3.5 GeV/c) in order to minimise beam particle scattering.

CLOUD will measure processes over the full range of tropospheric and stratospheric conditions. At ground level, the average GCR intensity is about $0.02\text{ cm}^{-2}\text{s}^{-1}$, whereas at altitudes of 15–20 km it is about a factor 100 larger, varying between about 0.8 and $2.3\text{ cm}^{-2}\text{s}^{-1}$ depending on geomagnetic latitude (Fig. 3a).

The maximum required *time-averaged* beam intensity is therefore about $10 \times 2 = 20\text{ cm}^{-2}\text{s}^{-1}$. The beam is spread over a large transverse area of $30\text{ cm} \times 30\text{ cm} \simeq 1000\text{ cm}^2$ in order to duplicate the quasi-uniform GCR irradiation, as closely as possible, over the fiducial volume. This is achieved by defocusing the quadrupole magnets in the T11

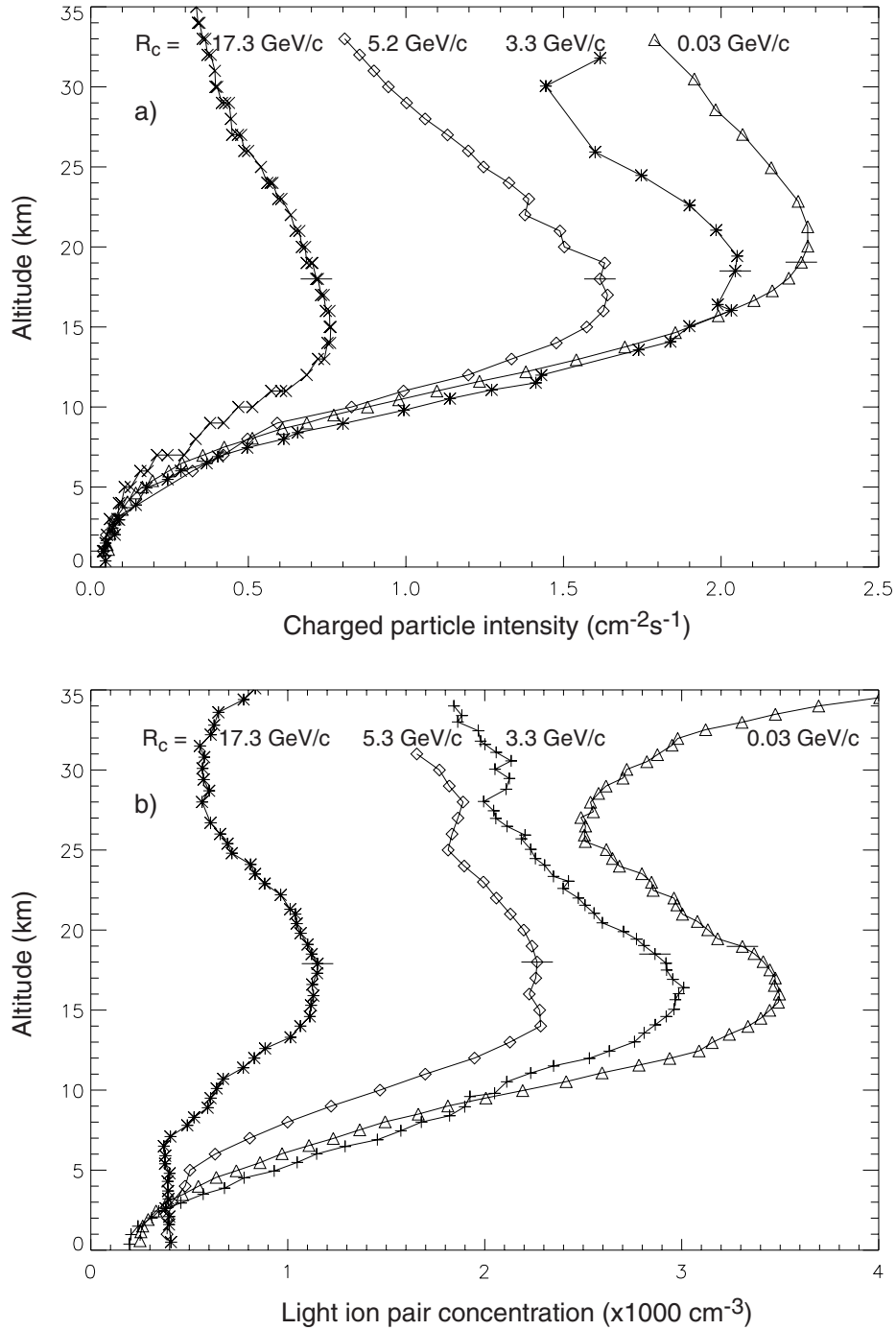


Figure 3: a) The charged particle intensity and b) the small ion pair concentration vs. altitude, measured at several latitudes with cutoff rigidities, R_c , as indicated. The data were recorded by Lebedev Physical Institute [3] in or near 1990, corresponding to a sunspot maximum (but without solar proton events), i.e during a cosmic ray *minimum*. The horizontal bars show the typical experimental statistical errors.

beamline. The time-averaged maximum beam intensity is then $20 \times 1000 = 2 \cdot 10^4 \text{ s}^{-1}$. If we assume a 0.5 s beam pulse from the CERN PS every 5 s, then the maximum beam intensity is $5 \times 2 \cdot 10^4 = 10^5$ /pulse. This is comfortably within the maximum performance of 7×10^5 /pulse for the T11 beamline at 3.5 GeV/c, assuming 2×10^{11} protons/pulse on the target.

The *minimum* beam intensity (apart from beam-off) is $1 \times$ the natural GCR radiation at ground level. This is a factor 1000 below the maximum required intensity (a factor 100 for the atmospheric attenuation and a factor 10 for $1 \times$ the GCR intensity rather than $10 \times$), i.e. a time-averaged intensity of 20 s^{-1} , or 100 /pulse, assuming 1 pulse every 5 s.

These beam estimates are summarised in Table 1.

Table 1: Summary of the minimum and maximum beam conditions for CLOUD. One beam pulse per 5 s is assumed, as well as a transverse beam size of $30 \times 30 \text{ cm}^2$. ‘GCR’ signifies the natural GCR intensity at the indicated altitude.

Simulated GCR intensity	Simulated altitude (km)	Beam intensity (particles/pulse)	Clearing field
$0.01 \times \text{GCR}$	0	0	on
$1 \times \text{GCR}$	0	0	off
$2 \times \text{GCR}$	0	10^2	off
$10 \times \text{GCR}$	0	10^3	off
$0.01 \times \text{GCR}$	10	0	off
$1 \times \text{GCR}$	10	10^4	off
$10 \times \text{GCR}$	10	10^5	off

2.2 Beam simulations

The calculations in §2.1 provide useful estimates of the beam requirements for CLOUD. However they under-estimate the actual beam requirements since they take no account of diffusion losses of ions to the chamber walls or of ion-ion recombination. We have therefore performed a 3-dimensional simulation which includes these effects. The results are shown in Figs. 4–7 and are described below.

GCR (no beam) conditions: The equilibrium ion pair concentration due to the background GCR flux¹ is about 500 cm^{-3} averaged over the cloud chamber volume (Fig. 5b). This value is slightly higher than typical measured values at ground level (Fig. 3b) since atmospheric aerosols scavenge small ions. The equilibrium concentration is reached after about 10 minutes (Fig. 4b shows a typical time evolution)—which is characteristic of small ion lifetimes in the atmosphere. The mean ion pair concentration can be readily

¹The GCR flux will be monitored by roof of recuperated plastic scintillation counters over the CLOUD facility.

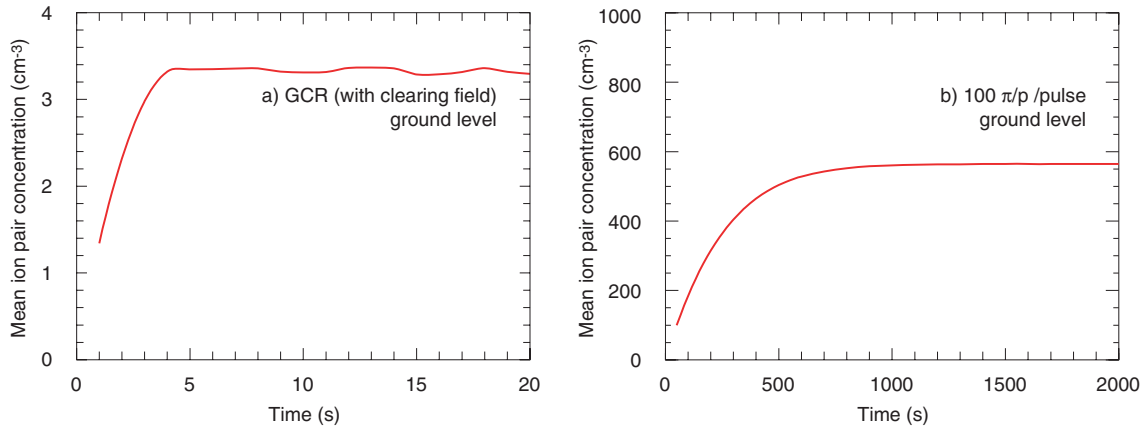


Figure 4: Mean ion pair concentration in the cloud chamber vs. time for the ambient GCR flux and a) no beam and clearing field on, and b) 100 particles /pulse ($\times 1$ pulse per 5s) and clearing field off. The chamber conditions correspond to aerosol-free air at ground level (293 K and 101 kPa). The ion pair concentration is assumed to be zero at $t=0$.

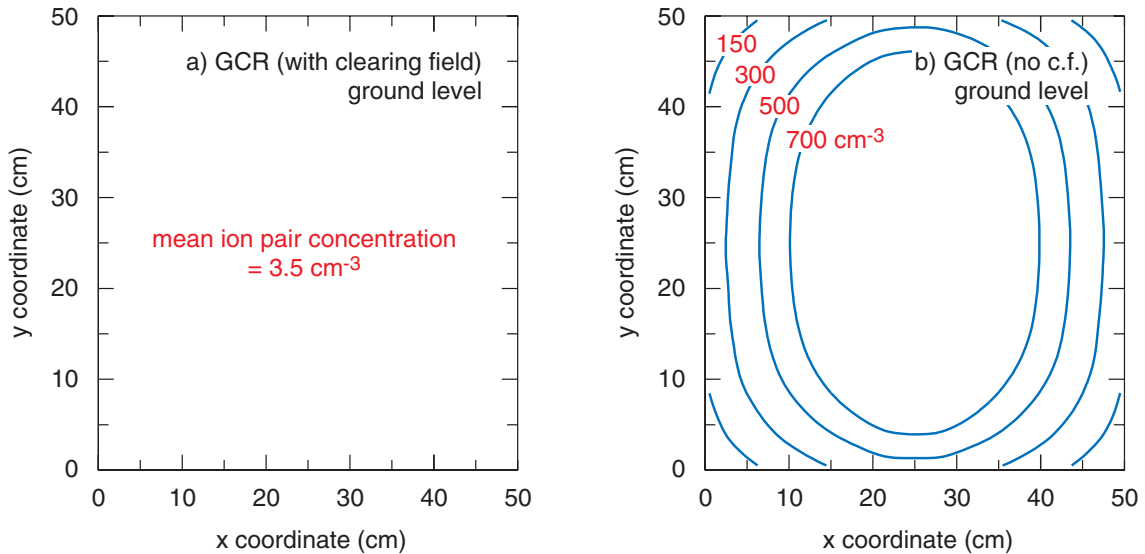


Figure 5: The equilibrium ion pair concentrations in the cloud chamber for no beam and the ambient GCR flux, a) with clearing field, and b) without clearing field. The chamber conditions correspond to aerosol-free air at ground level (293 K and 101 kPa). The projections show a central slice through the chamber in the vertical plane, with the beam axis along $y = 25$ cm.

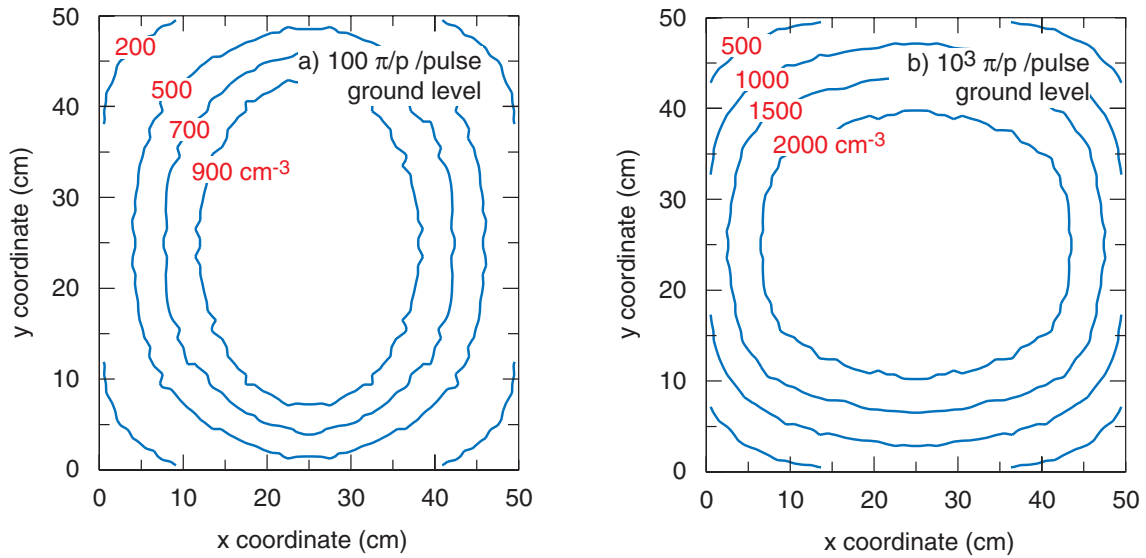


Figure 6: The equilibrium ion pair concentrations in the cloud chamber for the ambient GCR flux and a beam of a) 100 particles /pulse ($\times 1$ pulse per 5s), and b) 10^3 particles /pulse. The chamber conditions correspond to aerosol-free air at ground level (293 K and 101 kPa).

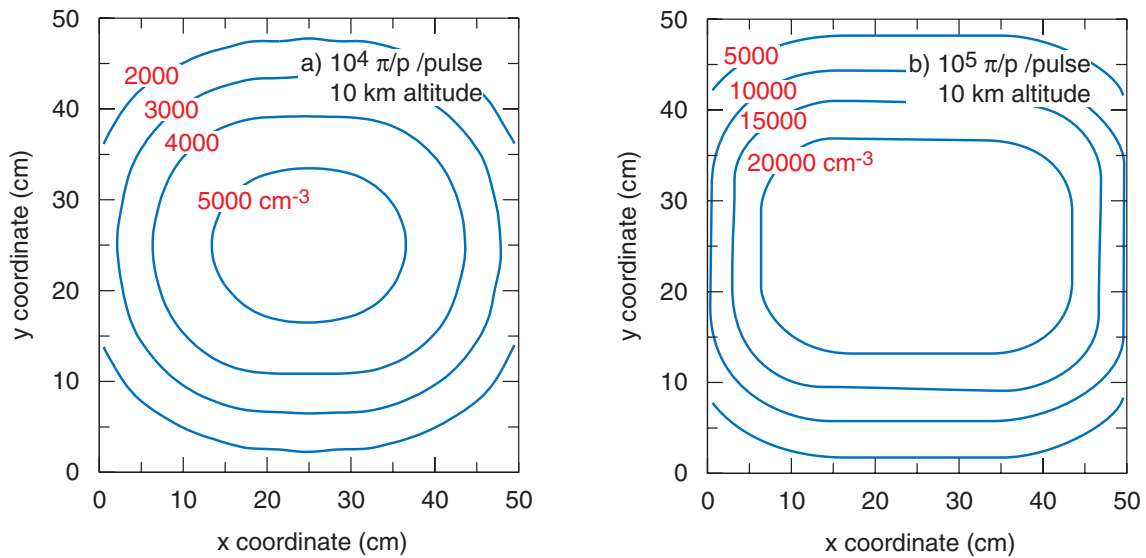


Figure 7: The equilibrium ion pair concentrations in the cloud chamber for a beam of a) 10^4 particles /pulse, and b) 10^5 particles /pulse. The chamber conditions correspond to aerosol-free air at 10 km altitude (223 K and 26 kPa).

reduced below the natural GCR level by turning on the clearing field. With 1 kVm^{-1} electric field, small ions are cleared from the cloud chamber in 4 s, and this reduces the mean ion concentration to about 1% of the atmospheric values at ground level (Figs. 4a and 5a). The clearing field can therefore be used very effectively to turn off ion-induced processes in the cloud and reactor chambers, since the ion-mediated effects generally occur on timescales that are long (several minutes to hours) compared with the clearing time. Note that, depending on their size, charged aerosols are not swept out by the clearing field due to their low mobilities.

Ground-level conditions: Data taken without beam and with various clearing field settings will provide the lowest ionisation measurements at ground level conditions. For higher ionisations at ground level conditions, the beam is used. The expected ionisation concentrations for 100 particles /pulse and 10^3 particles /pulse are shown in Figs. 6a) and b), respectively, assuming 1 pulse /5 s. These beam intensities produce rather modest increases in the ion pair concentrations since the cross-sectional area of the cloud chamber illuminated by the beam is about a factor 2.5 less than that illuminated by GCR. To obtain the desired factor 10 increase in ion pair concentration above atmospheric values requires a beam intensity of about 4×10^3 particles /pulse.

10 km conditions: The expected ionisation concentrations for 10^4 particles /pulse and 10^5 particles /pulse at 10 km conditions are shown in Figs. 7a) and b), respectively. The mean ion pair concentrations at these high altitudes are about 3000 cm^{-3} for high geomagnetic latitudes (Fig. 3b). These beam intensities therefore reasonably well cover the desired range, although a maximum beam intensity of about 2×10^5 particles /pulse is required to reach $10\times$ the natural GCR level at 10 km altitude. Finally we note that the ground-level background GCR in CLOUD decreases in significance for increasing altitude conditions, and is essentially negligible ($\sim 1\%$) at 10 km conditions.

2.3 Alternative ionisation sources

The basic goal of CLOUD is to duplicate atmospheric and cosmic ray conditions in the laboratory. Cosmic rays consist mostly of pion and electron secondaries in the upper troposphere, and decay muons near ground level. The primary cosmic rays mostly interact in the ($\sim 2\lambda$) material above the tropopause. Therefore, essentially throughout the troposphere, charged cosmic rays comprise minimum ionising particles.

The requirements of the ionisation source for CLOUD are as follows:

- Capability to deposit a precisely known quantity of ionisation at a precisely known location inside the cloud chamber and reactor chamber.
- An ionisation density (dE/dx) that is characteristic of minimum ionising particles.
- Easily adjustable in intensity over the required range of $1\text{--}10\times$ the natural cosmic ray intensities found in the troposphere—a factor of about 1000.
- Ability to traverse the walls and liquid cooling layers of the cloud chamber and reactor chamber. This sets a minimum energy for a particle beam of about $1 \text{ GeV}/c$, taking multiple Coulomb scattering also into account.

- Known timing. This is necessary for the study of fast processes and also for ice nucleation studies to distinguish between deposition nucleation and freezing nucleation.

Other sources of ionising radiation include ultraviolet (UV) radiation, radioactive sources and X ray sources. UV radiation is excluded since it induces photochemical reactions among the trace gases. In the case of radioactive sources, α emitters are excluded by their high ionisation density and short range, and β emitters are excluded since they cannot be placed inside the cloud chamber, and their range is insufficient to penetrate the chamber walls.

Gamma radioactive sources are impractical; they would need to be distributed around the outer surfaces of the cloud chamber and reactor chamber, and even then would provide imprecisely-known and non-uniform ionisation in the fiducial volumes. The maximum required intensity is equivalent to 1000 times the ground-level GCR intensity at a distance of about 1 m from the source. This represents a significant radiation hazard and poses handling and safety problems. Furthermore it is difficult to adjust the intensity of a gamma source over the required range, and there are no timing capabilities. X ray sources have similar limitations, with the added problem that, since the range of X rays is shorter, large absorption and non-uniformities result from the detector material.

A careful search of the literature [4] has uncovered many little-known laboratory studies of ion-induced effects on aerosol formation since the 1960's using traditional ionisation sources (e.g. refs. [5, 6, 7]). Members of our collaboration have also studied these processes more recently using X rays and α particles from ^{241}Am sources [8]. Although some useful results have been obtained, these studies have generally been unable to characterise the aerosol processes adequately. There are two reasons for this:

1. Lack of control of the ionisation at near-atmospheric intensities.
2. Non-uniformities of deposited ionisation. We have shown [9] that local variations of ion density (for example, from an α source) give rise to non-linear aerosol charging effects, which will directly affect ion-induced aerosol processes. This makes it difficult to relate results obtained with such sources to the real atmosphere.

The limitations of traditional sources have hindered further progress with these experiments.

In contrast, a GeV beam from a particle accelerator ideally matches the requirements of a well-defined and reproducible ionisation source. It can deliver a precise quantity of ionisation with a precisely known spatial distribution, and at an exactly known time. Until now, as far as we know, no one has used an accelerator beam for such studies. By combining this ideal ionisation source with an advanced detector of unrivalled capabilities, CLOUD offers excellent prospects for a breakthrough in ion-aerosol-cloud research.

2.4 Experimental area layout

At its meeting on 6 September 2000, the SPSC emphasized the importance of maximising the remaining free space in the T11 beamline after CLOUD is installed, in order to maintain the highest flexibility for future detector tests. Together with PS Division staff we have therefore developed a new beam layout, which is shown in Figs. 8 and 9. By

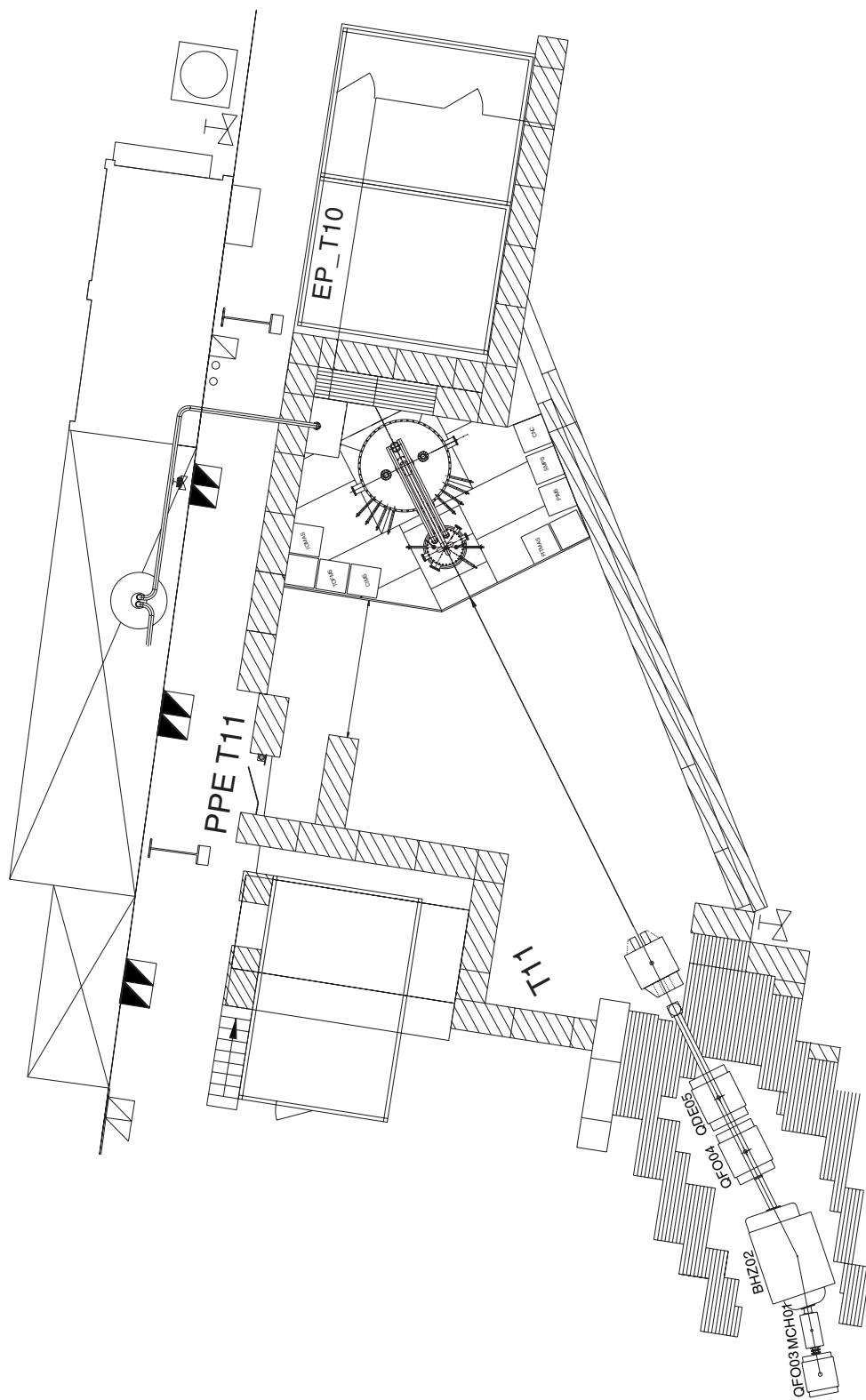


Figure 8: Updated experimental area layout of the CLOUD facility at the CERN PS in the T11 beamline of the East Hall.

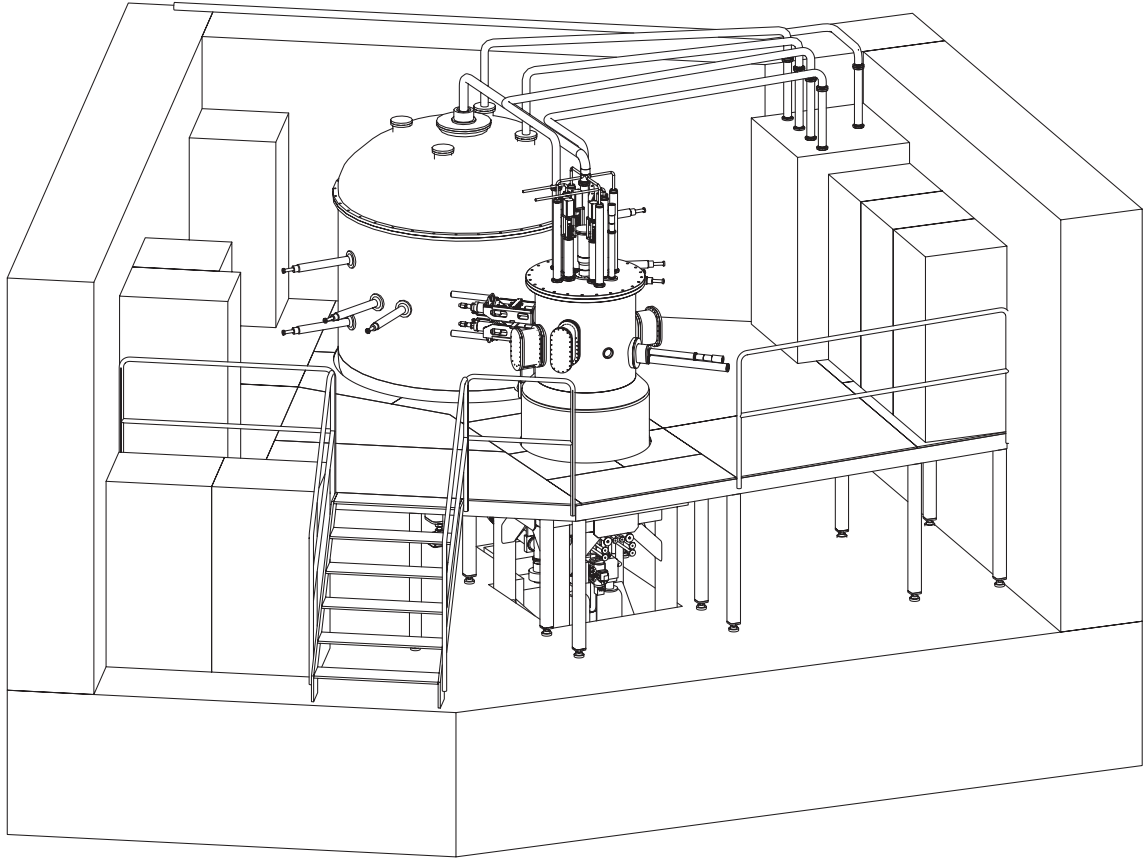


Figure 9: Perspective view of the CLOUD facility in the T11 beamline of the East Hall

re-configuring the concrete shielding blocks at the end of the present T11 beamline and by minimising the footprint of the facility, the free space along the beamline will decrease by only 1 m after CLOUD is installed (from the present 11 m to 10 m).

3 Background measurements in the East Hall

Another question raised by the SPSC concerned the ambient background level in the East Hall. Accordingly we have measured the atmospheric small ion concentrations and variability in the East Hall during operation of the CERN PS.

3.1 Instrumentation

The measurements were performed with a Programmable Ion Mobility Spectrometer (PIMS) which we have developed in Reading [10]. This device involves a sampling cylinder in which the ions are drifted onto a well-insulated axial electrode under the influence of an electric field. The PIMS is ventilated by a fan which draws air through the cylinder at about 2 ms^{-1} . A sensitive current amplifier integrates the ion charges collected. The small ion concentration is directly proportional to the air conductivity, which is calculated from

the measured current, and the sampling tube's geometry and ventilation rate. Typical currents are a few 100 femtoamperes. The PIMS is calibrated by means of two operating modes—ion-induced voltage decay and direct ion current measurement—under microprocessor control [11]. A rigorous calibration procedure has been developed for atmospheric operation under demanding and variable environmental conditions [4], including a new *in situ* method for direct calibration of the current amplifier [12].

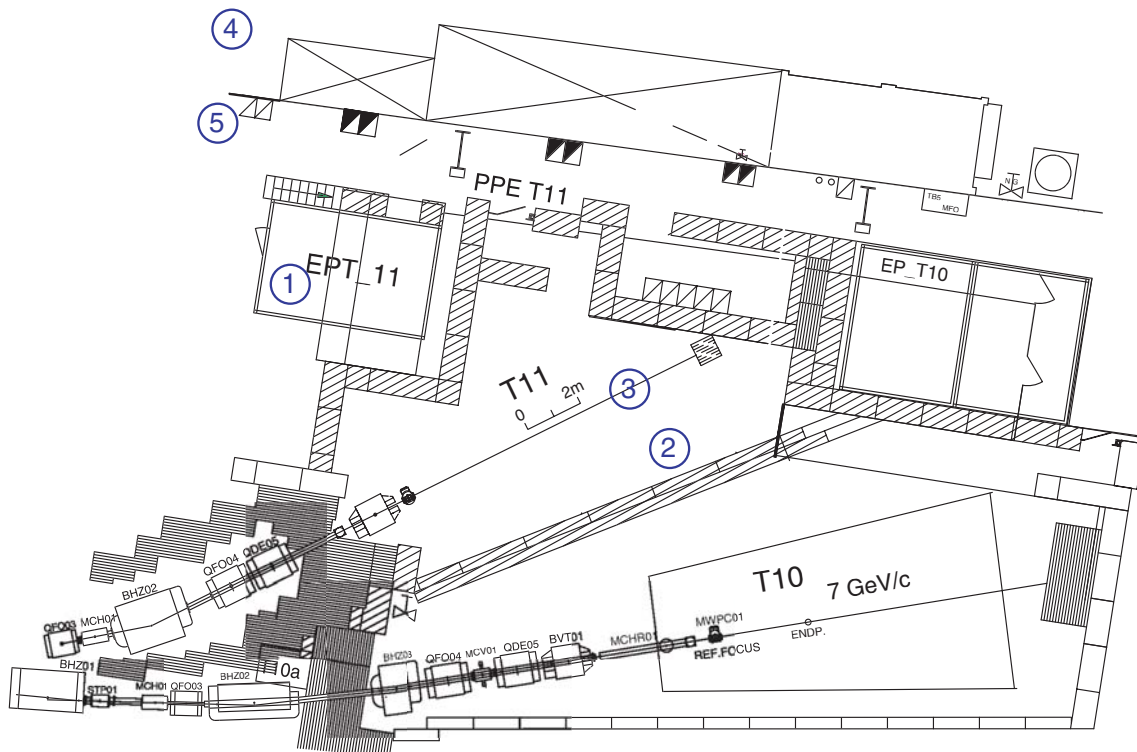


Figure 10: Locations of the five measurement sites in the CERN East Hall.

3.2 East Hall tests

Atmospheric small ion concentrations were measured at various East Hall locations, as indicated in Fig. 10, on 5th October 2000 from 11h30-17h00 local time. During this time the CERN PS was delivering about 3 pulses per supercycle onto the East Hall Target North (the target for the T9, T10 and T11 beamlines) at an average intensity of 2×10^{11} protons/pulse. During the tests the T11 beam was off and the adjacent T10 beam was on.

At each site, the PIMS instrument was operated using an automated sequence of voltage decay measurements (sampled at 2 Hz) and current measurements (the microprocessor calculates averages of ten 1 Hz samples) every three minutes. The system leakage current and op-amp input offset voltage were also sampled to compensate the measured ion currents for temperature-dependent effects [10].

Ion measurements were made for approximately 30 minutes at each location. The negative air conductivity and negative ion concentration were calculated as described in [4], and are presented in Table 2. The calculation of ion concentration assumes that the negative small ions have a mean mobility of $1.9 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}$ [13].

Table 2: Measurements of the atmospheric negative ion conductivity and negative small ion number concentration in the East Hall. The negative ion concentrations are approximately equal to the ion pair concentrations. During all measurements the PS was operating and delivering beam to Target North (the T9/10/11 target) and the adjacent secondary beam (T10) was on.

No.	Location	Conductivity ($\times 10^{-15} \text{ S/m}$)		Ion concentration (cm^{-3})	
		Mean	σ	Mean	σ
1	T11 control room	12.2	5.6	401	184
2	T11 beam area, 3m off-axis, beam off	8.1	6.6	266	217
3	T11 beam axis, beam off	12.9	6.3	424	207
4	Outside East Hall	13.5	5.0	444	197
5	Inside East Hall	14.1	6.0	464	197

Typical atmospheric air negative conductivities (which are directly proportional to the small ion concentrations) in urban air at Reading are around $13 \cdot 10^{-15} \text{ S/m}$, with short-term (of order tens of minutes) variability up to 100% (see, for example, Fig. 37 on p. 58 of the CLOUD proposal). These conductivities correspond to around 400 ion pairs cm^{-3} , and are comparable to ground-level values measured elsewhere (e.g. Fig. 3b). The values measured in the East Hall are quite similar, and show no evidence for any significant increase in the ambient ion background. These measurements provide a realistic test of backgrounds for CLOUD since air is the active material in the detector and ion number concentration is the parameter of interest. We conclude that low background conditions exist in the East Hall for the CLOUD studies.

4 Conclusions

We are proposing a European facility at CERN where atmospheric scientists can investigate the role of natural ionisation in aerosol and cloud formation. The concept of a facility is appropriate for the comparatively large and complex experimental programme of CLOUD extending over several years, and in view of the need for flexibility in a field where rapid progress may be expected in the next few years.

CLOUD's requirements include a variable particle beam, techniques derived from CERN's bubble-chamber experience, exacting cryogenic temperature control, and the skills in integration, experimental management and data-processing for which CERN is well known. For all these reasons, CERN is uniquely suited to host the facility.

The facility would use a 3.5 GeV/c secondary beam from the CERN PS in the T11 beamline of the East Hall. Beam intensities between 100 and 10^5 particles/pulse are required to cover the desired range of $1-10 \times$ the cosmic ray intensities found in the atmosphere. We have experimentally verified low background conditions in the East Hall for the proposed studies.

The CLOUD detector would occupy a permanent space at the end of the T11 beamline, reducing the free space available for test experiments from the present 11 m to 10 m. CLOUD would take data during about one half of the yearly operation of the East Hall, leaving the T11 beamline available for test experiments during the remaining time.

Unique in the world, this facility will open up an essentially new field of atmospheric research. Its primary task, as described in the CLOUD proposal, is to pursue the question of how cosmic rays may influence cloud microphysics. If clouds respond to the solar variations that modulate the cosmic rays reaching the Earth, there are consequences for the evaluation of climate change. To settle the issue, one way or the other, is therefore of urgent global importance.

Acknowledgements

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