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History of the European Muon Collaboration (EMC)

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Abstract

The European Muon Collaboration (EMC), formed in the years 1972–1974, was one of the first large experimental particle physics collaborations with more than 100 physicists. Its aim was to study the quark structure of the nucleon through deep inelastic muon scattering. Two seminal discoveries were made; the EMC effect and the spin crisis. In this paper the history of the collaboration from beginning to end is described. The appendices describe some of the difficulties met during the development and performance of the experiments as well as a description of some of the social interactions in the collaboration.

Keywords

Physics collaborations; particle physics; quark structure; EMC.

Terry Sloan

Contents

1 Introduction

The EMC performed experiments to study the interactions of muons with fixed targets (see Appendix A for lists of participating physicists). The muon beam was produced from the interactions of the 400 GeV protons accelerated in the Super Proton Synchrotron (SPS) at CERN. The particles resulting from the interactions of the muons in a fixed target were studied by the collaboration. The fixed targets were free protons both unpolarized and polarized, deuterium and various nuclear targets. The experimental data were taken between the years 1978 and 1985.

Comparison of the scattering rates from the deuterium and nuclear targets showed that the quark structure of the bound nucleon is different from that of the free nucleon. This became known as the EMC effect. This was the first seminal discovery by the Collaboration.

Measurements with polarized protons showed that, at higher four-momentum transfers, the spin of the proton was not concentrated in its valence quarks in contrast to the situation for static protons. This was the second seminal discovery, becoming known as the spin crisis.

Neither of these discoveries has, thus far, been satisfactorily explained.

In this paper the history of the development of the collaboration is charted from the beginning in 1972 to the end of its activities in 1989. For a review of the physics results from the EMC see Ref. [1].

2 The early history

The EMC grew out of the Tirennia meetings [2] arranged by the European Committee for Future Accelerators (ECFA) in 1971 and 1972. The purpose of these meetings was to discuss the exploitation of the 400 GeV SPS planned at that time to be built at CERN. The internal quark structure of the proton had just been revealed by the discovery of deep inelastic electron–nucleon scattering by the DESY Group [3] and by the SLAC Group [4]. This subject was therefore high on the agenda of the Tirennia meetings for experiments with lepton beams at the SPS. The discovery of deep inelastic scattering would go on to earn the 1990 Nobel Prize for J.I. Friedman, H. W. Kendall, and R.E. Taylor.

It was soon realized that better muon beams than electron beams would be available at the SPS [5] for two reasons. First, muon beams at the SPS would have higher intensity and higher energy than electron beams. Second, experimental sensitivities could be further enhanced by using longer targets in a muon beam than in an electron beam since the complications due to external bremsstrahlung were much smaller with muons.

Two proposals for muon beams at the SPS were presented at the Tirennia meetings: one from Friedhelm Brasse, Joerg Gayler, Juergen May, and H.J. Behrends (DESY) [6] and the other from Roger Clifft, Erwin Gabathuler, and Tom Aitken (Daresbury) [7]. The purpose of these beams was to study deep inelastic scattering in greater detail. A parallel proposal to use an electron beam for such studies was also received from Juergen Drees [8], who had been a member of SLAC Group which discovered deep inelastic scattering.

The interested parties named above together with a French group from Orsay (J.J. Aubert and F. Vanucci), and an Italian group from Torino (M. I. Ferrero), then joined together to finalize the design of the muon beam and to propose an experimental programme. The collaboration grew from these beginnings. The first meeting of the interested parties took place at DESY in Hamburg on 1 December 1972 with 15 participants. The apparatus needs were discussed at this meeting and the use of a vertex magnet with streamer chamber and a polarized target were first mentioned. It was decided at this meeting that a letter of intent should be written, organized by the founding fathers of EMC, Friedhelm Brasse and Erwin Gabathuler (pictured below in Fig. 1).

Fig. 1: (Left-hand panel) Friedhelm Brasse at his retirement in 1994 from DESY (image credit DESY). (Right-hand panel) Erwin Gabathuler discussing the EMC experiment in July 1977 (image credit CERN, CERN-PHOTO-7707075).

The second meeting of the growing collaboration took place at Daresbury Laboratory on March 2, 1973 with 32 participants. It was agreed at this meeting that Erwin Gabathuler should be contact man for the group for one year.

Meetings of local groups also took place between the main collaboration meeting to coordinate the work towards developing a physics programme and designing the necessary apparatus. For example meetings took place for UK participants at Daresbury Laboratory on 20 December 1972 and 30 January 1973.

The physics programme took shape at these and at subsequent meetings, where detailed reports were discussed. The proposed physics programme included the study of the structure of the nucleon using inclusive muon scattering on hydrogen and deuterium targets, both polarized and unpolarized. In addition, it was proposed to study the particles produced in deep inelastic scattering to investigate the properties of the quarks ejected from the nucleon in the scattering process. A programme was also proposed using a calorimeter target which became known as the STAC (sampling total absorption calorimeter). The motivations for the latter target were to increase the data taking rate since the STAC was made mainly of iron which is much denser than hydrogen and deuterium. The greater sensitivity from the higher counting rates due to the increased luminosity allowed deeper probing of the structure of the nucleon. It also allowed searches for other unexpected phenomena through multi-muon production.

Between 1972 and 1974 the collaboration adopted the name European Muon Collaboration, or EMC. During this period Erwin Gabathuler and Roger Clifft moved to CERN to expedite the writing of the proposal and to coordinate the building of the apparatus and infrastructure once the proposal was accepted.

The start point for the design of the apparatus was based on a 1970 model for a full coverage spectrometer. This involved multiple spectrometer magnets tuned to detect particles in both the forward direction (positive Feynman x) and backward direction (negative Feynman x) in the centre of mass frame. It was soon realized that a large part of the physics programme to be addressed could be achieved with a much simpler spectrometer using a single magnet which detected the particles emitted in the forward direction in the centre of mass system. For this reason the initial experiment adopted the single magnet solution as the first stage of the experiment. This became known as the Forward Spectrometer experiment. The open nature of the Forward Spectrometer allowed the hadron distributions in the forward hemisphere (positive Feynman x) to be measured for hydrogen and deuterium targets. The trigger to select interesting events, based only on the detection of the muon, would be formed from a series of scintillation counter hodoscopes to detect the scattered muon using a novel programmable matrix coincidence system designed by Werner Flauger of DESY [9].

The collaboration wished also to study particle emission at more backward angles in the centre of mass. This was achieved by later adding a vertex detector with a streamer chamber and an array of Cerenkov counters to detect and identify particles produced in the backward region in the centre of mass frame (negative Feynman x). This became the second stage of the experiment.

To study polarized protons a special target arrangement was necessary. It was realized that the asymmetries would be small and difficult (but not impossible) to measure. To avoid false asymmetries due to differences in the apparatus efficiencies it was proposed to measure the count rate differences between the two states of polarization of the proton at the same time. This necessitated two very large polarized targets to be built and simultaneously exposed to the beam. It was decided to have two sequential targets along the beam direction with opposite proton polarizations in each target. The polarizations would be inverted from time to time to cancel any time dependent acceptance changes. The target (i.e., polarization state) which produced the scattering could be identified from the position along the beam of the scattering vertex.

A letter of intent (LOI) which outlined the physics programme was then submitted in June 1973 to the CERN oversight committee (the SPSC) [10]. Meanwhile, a muon programme was also taking shape at Fermilab in the USA. The EMC clearly feared that the latter programme would be ready earlier than that at CERN and would therefore be able to scoop any discoveries to be made. An addendum to the LOI [11] was submitted in November 1973 to say that EMC would prioritize the Forward Spectrometer part of the experiment with the hydrogen, deuterium, and STAC targets.

The final proposal for the experiment included both the Forward Spectrometer and the vertex detector with emphasis on the Forward Spectrometer work. It was written in a frenetic period between Easter and 1 July 1974. The proposal became known as the White Book (CERN/SPSC/74-78) dated 1 July 1974 [12]. The Forward Spectrometer part of the proposal was approved by the SPSC and the experiment given the number NA2 (NA for the North Area at CERN where the experiments would be situated). Appendix B gives the details of the building of the different sections of the apparatus.

The decision on the vertex detector was deferred. One reason for the deferral was that CERN needed to take an overview of all the vertex detector proposals of which there had been several for other experiments as well as EMC. Nevertheless, interest in the vertex detector remained strong within the EMC and a memorandum was submitted to the SPSC [13] in October 1975. The memorandum reiterated the EMC interest in adding a vertex detector to the Forward Spectrometer. This was eventually approved by the SPSC and given the number NA9. Eventually two vertex magnets were built, one for the EMC experiment NA9 and one for another experiment.

3 The building of the forward spectrometer apparatus and NA2 data taking

The muon beam [14, 15], experimental hall (EHN2 at CERN) and the apparatus were constructed and installed between the years 1974 and 1978 and the collaboration grew to about 100 physicists. See Appendix C for a description of the tuning of the beam and see Fig. 2 for a picture taken in EHN2 during the apparatus installation.

Fig. 2: The picture shows the EMC apparatus being assembled in EHN2. The large black object is one half of the H2 Scintillation calorimeter hodoscope (see below). The muon beam passes from right to left in the picture through the semicircular hole in the H2 hodoscope (the circle being completed by the second half of H2). The block of iron painted green is the absorber for strongly interacting particles. The weakly interacting muons pass though this absorber. The blue objects (far left) are the magnets for a different experiment (The Bologna, CERN, Dubna, Munich and Saclay (BCDMS), NA4 Experiment), being assembled downstream of the EMC apparatus. This experiment took data at the same time as the EMC (image credit CERN,CERN-PHOTO-7709559X).

To obtain funding for the experiment much work had to be done with the funding authorities in each country with a participating institution as illustrated in Fig. 3. Proposals for funding had to be submitted to the funding authorities in each country.

Fig. 3: Erwin Gabathuler (left) in Feb. 1978 explaining the EMC apparatus to Shirley Williams, the then UK Secretary of State for Education. Others in the picture are Michael Crowley-Milling (3rd from left), Godfrey Stafford (4th from the left), Director of the UK's Rutherford Laboratory, two unknown persons (5th from left), and John Adams (far right) the then Director General of CERN (image credit CERN, CERN-PHOTO-7802613X).

The apparatus was ready to take data in 1978. Fig. 4 shows a diagram of the Forward Spectrometer apparatus and Fig. 5 shows a picture of the hall in which the experiments were performed (EHN2). For a detailed description of the apparatus see EMC publication 6.

Data taking began in running period P5B of the SPS in 1978 with the STAC target. This continued into running period P6. The STAC target was then removed and replaced by a 6 m long hydrogen target, the hydrogen later being replaced by deuterium.

The Forward Spectrometer data were taken between the years 1978 and 1980. To analyse the data, the collaboration split into several groups. The multimuon group analysed events with multiple muons. Two groups analysed the single muon inclusive scattering events to determine the structure functions of the nucleon; one for the structure functions from heavy nuclei using the STAC target and one for the data from the hydrogen and deuterium targets. Another analysis group was formed to study inclusive hadron production. Many publications resulted from these groups based on the Forward Spectrometer data (see list of EMC publications).

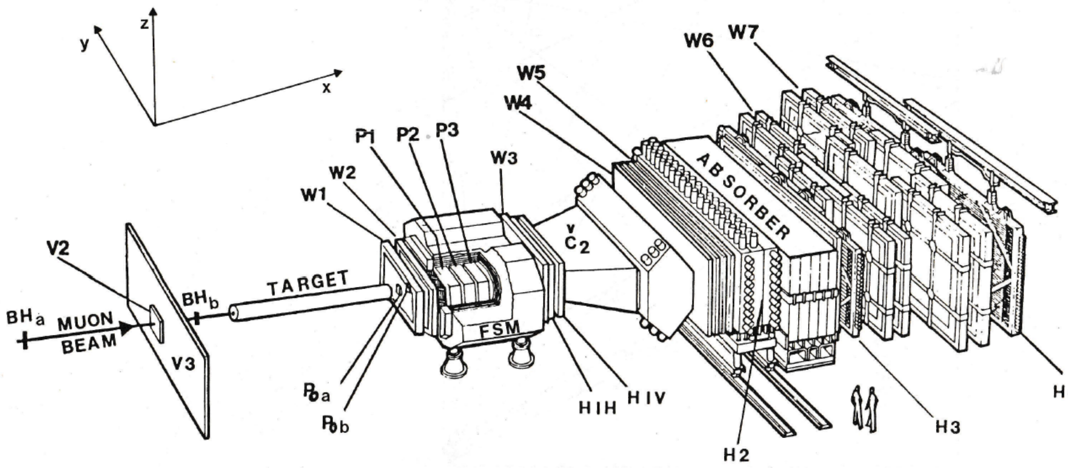

Fig. 4: An artist's impression of the full EMC Forward Spectrometer apparatus. The code is FSM = the Forward Spectrometer magnet, C = Cerenkov counter to allow particle identification, V = veto counters to reject events from the beam halo, P = multi-wire proportional chambers, W = drift chambers. H = scintillation counter hodoscopes mainly to detect and select muons scattered from the target (the trigger). The absorber removes particles except muons allowing the scattered muon to be selected for the trigger by the scintillation counter hodoscopes H3 and H4 in coincidence with the hodoscope H1. The drift chambers and multiwire proportional chambers allowed precise measurement of the trajectories of the particles in each event (picture from CERN preprint CERN-EP-80-134).

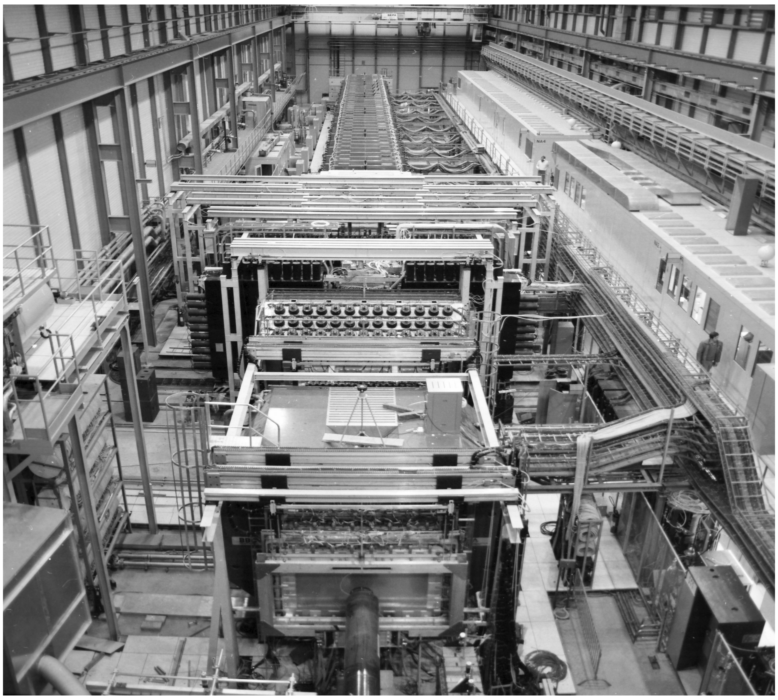

Fig. 5: A photograph of EHN2 looking in the direction of the muon beam. The EMC Forward Spectrometer is in the foreground and the BCDMS experiment downstream of it. The cabins on the right housed the experimental control rooms. The muon beam passes from the lower centre of the picture to the top. At the bottom of the picture, the long narrow cylindrical vessel for the EMC hydrogen/deuterium target can be seen just before the drift chambers W1, W2 which were situated at the mouth of the Forward Spectrometer magnet. The long line of magnets in the upper quarter of the picture belonged to the BCDMS collaboration (experiment NA4) which shared the muon beam with EMC. The two experiments took data simultaneously since the muon beam is almost unaffected by the upstream experiment (image credit CERN, CERN-PHOTO-8002006).

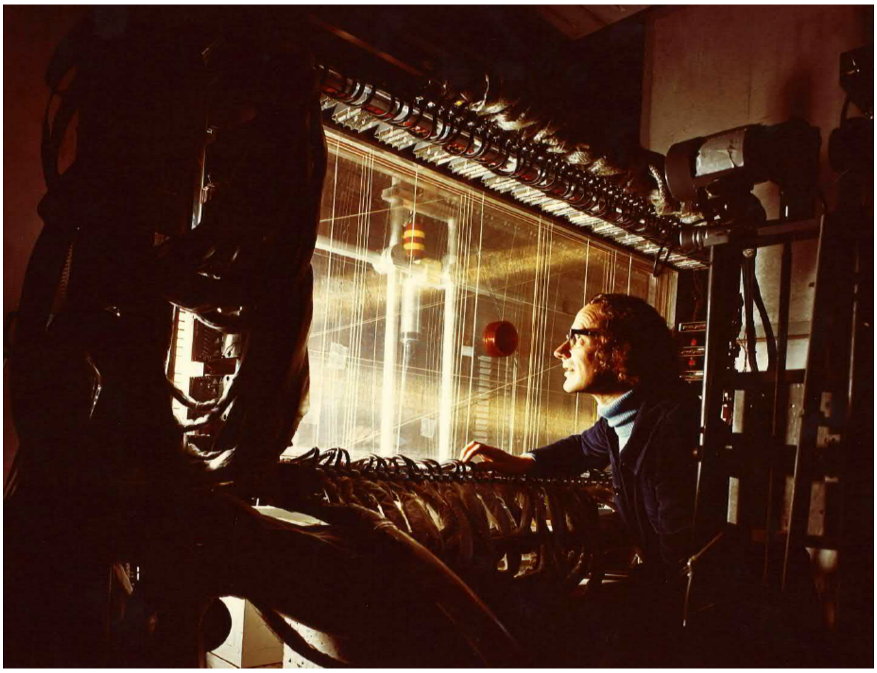

Fig. 6: The picture shows Roger Clifft working on one of the proportional chambers which were situated within the Forward Spectrometer magnet P1, P2, P3. The central brown region is the desensitized area through which the muon beam passed (image credit CERN, photo X-611-9-77).

Comparing the structure functions from iron, measured using data from the STAC target, and those from the deuterium led to the startling discovery that the quark structure of nucleons bound in nuclei was different from that of free nucleons. This would be called the EMC effect by theoretical physicists. Afterwards, many theory papers were published on the effect, creating great interest in the nuclear physics community [16]. This was the first major EMC discovery.

The measured structure functions of the nucleon showed that the scaling factor of the strong interaction coupling constant of quantum chromodynamics (QCD) had a value of nearly 200 MeV (EMC publications 10,11,15,19,21,22,37,44, and 55). This was close to the modern accepted value and showed that the previously accepted value of more than 500 MeV from earlier experiments had been overestimated. Long discussions took place within the collaboration about the quoted systematic uncertainties on the structure function measurements. Some thought they were underestimated and sadly they were proved to be correct. Serious discrepancies emerged between the detailed values of the EMC structure functions and later measurements from other groups. These were found by comparing the EMC data with those from the BCDMS experiment [17] which was situated downstream of the EMC apparatus in the same experimental hall. For this reason, the EMC structure functions do not appear in the modern structure function graphs produced by later groups [18].

Logically, installation of the polarized target would have followed the completion of data taking with the STAC, hydrogen, and deuterium targets in 1980. However, it had proved a technological challenge to build the two polarized targets (see Appendix D), which were much larger than any previous target and used a novel material (ammonia, NH_3) which was richer in free protons than previous targets. The targets were not ready in time and the collaboration decided to go on to the next phase of running (NA9/28) and to return to the Forward Spectrometer configuration for the polarized target run at a later date.

4 The vertex spectrometer (NA9/NA28) experiment

In 1979 preparations for and the installation of NA9 and NA28 took on considerable importance. Several new groups joined EMC to complete these studies and the collaboration grew to be about 150 physicists (see Appendix A3 for the contributing physicists and participating institutions). Study of the hadron final states had been of special interest to many people. The apparatus was ready to take data by 1981 (for details of this apparatus see EMC publication 20 and Fig. 7).

The vertex detector was installed after the completion of data taking in 1980 during the winter shutdown of the SPS. A streamer chamber, built by the Munich group which joined for NA9, was used to detect the larger angle particles emanating from muon interactions in the target installed inside the vertex magnet. Several Cerenkov detectors were also used to identify the particle types.

Fig. 7 below shows a schematic diagram of the NA9 apparatus with the same code as in Fig. 4 for the Forward Spectrometer. The added vertex magnet and extra Cerenkov counters for particle identification can be seen.

Nuclear targets were also installed in the beam at a different location than the hydrogen target. A special microprocessor based trigger system had been proposed and installed. This used the vertex detector magnet and forward system as a focussing spectrometer and had been introduced to the collaboration by the Uppsala group. Segmented scintillator hodoscopes in the beam triggered on small angle muon scatters from the nuclear targets to allow measurements from scattering in nuclei down to low Q^2 (small scattering angle). Fig. 8 shows a photograph of a typical segmented scintillator hodoscope. This proposal had been approved by the SPSC and became experiment NA28. The trigger was novel since it had to pick out signal events in a high background region (the beam at a rate of 10^7 muons per second). The nuclear and hydrogen targets for NA28 and Na9, respectively, were in the beam simultaneously at different locations. The source of each scattering event could be reconstructed from the position of its beam vertex. The data from this experiment convincingly demonstrated shadowing of the virtual photon in a nuclear medium (see the EMC publications 62 and 66).

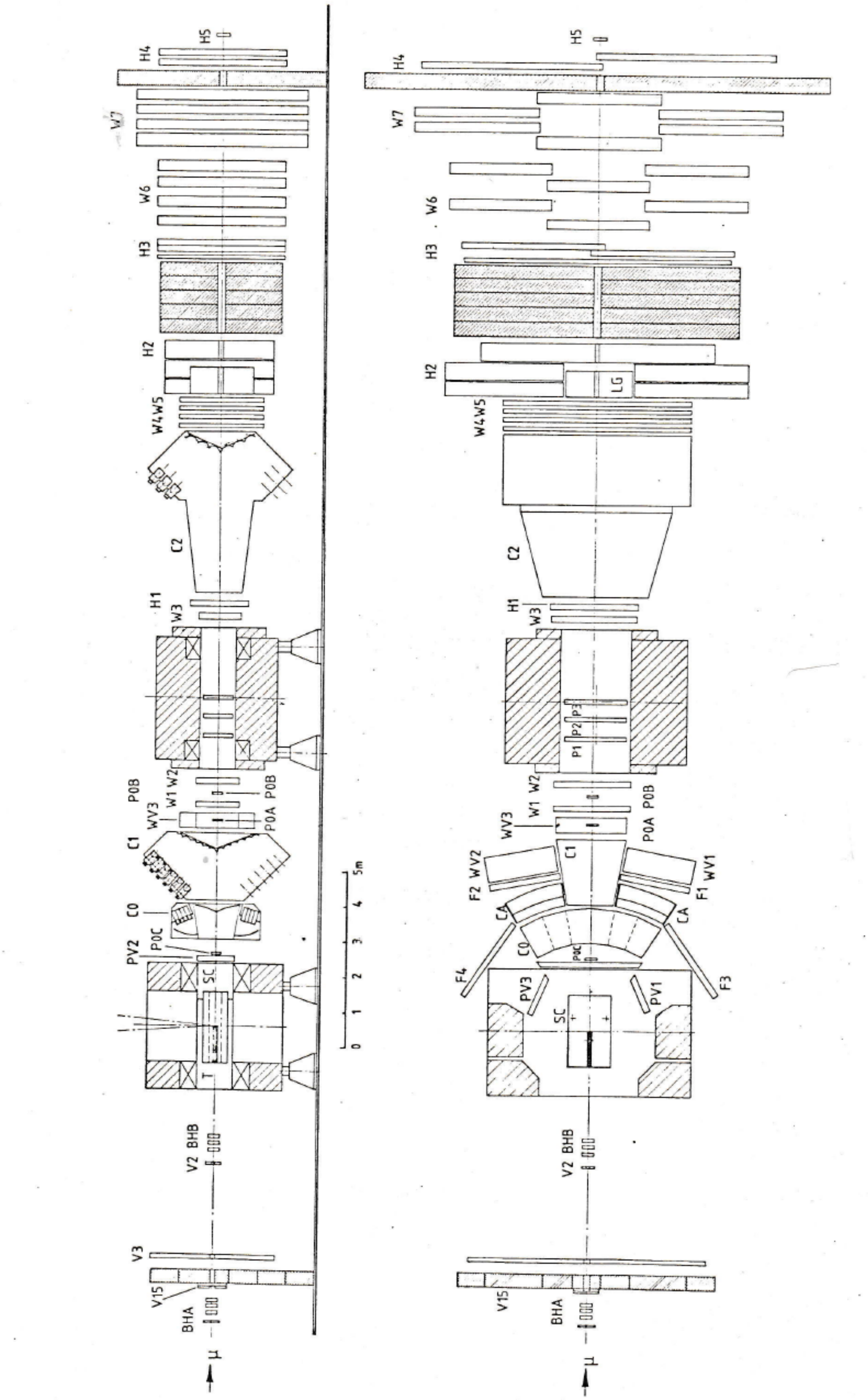

Fig. 7: A schematic diagram of the NA9 experiment. This shows the addition of the vertex magnet to the Forward Spectrometer system (see Fig. 4). This figure is taken from CERN preprint CERN-EP-82-160.

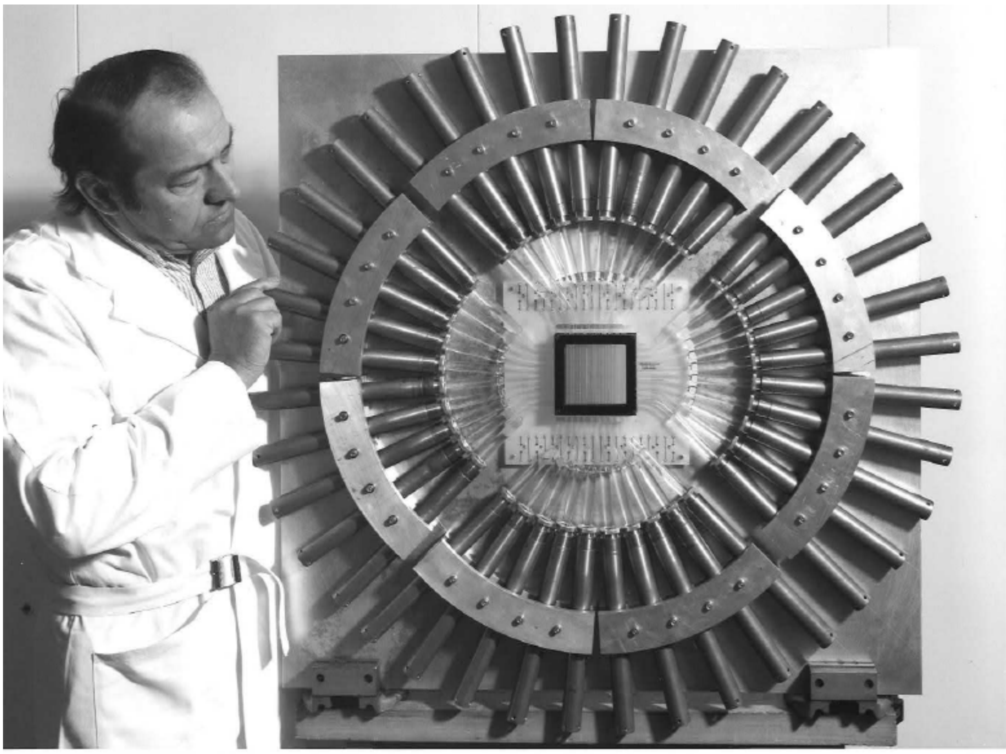

Fig. 8: One of the EMC segmented scintillator hodoscopes. The scintillation light from the scintillators in the black square is led to the photomultiplier tubes in the fan-like arrangement around the outside (image credit CERN).

In 1981 NA9/28 began taking data. In this period the observation (from NA2) that the structure function for nucleons bound in a nucleus differed from that for unbound nucleons, the EMC effect, was presented at the 1982 Rochester Conference in Paris, and published (EMC publication 22).

In 1982 there was a fire in the Forward Spectrometer magnet. The damage from the fire led to significant lost beam time by NA9/28, time which was needed for the necessary repairs (see Appendix E).

The main physics results from the NA9 experiment were the distributions of hadrons produced in deep inelastic scattering. These were used, together with the NA2 data, by the phenomenologists at Lund and Cambridge Universities to develop their models of fragmentation into hadrons of the quark ejected from the nucleon by the muon scattering process. The models eventually became known as Pythia and Herwig. These models would be extensively used in the subsequent generations of high energy physics experiments involving hadron production throughout the World.

5 The change to the polarized targets in 1984

The year 1983 saw the nominal end of NA9/28 running and the EMC was scheduled to return to the Forward Spectrometer configuration to perform the delayed polarized target experiment. However, many in the collaboration wanted to continue running NA9/28 basing their arguments on the fact that running time had been lost due to the fire and the difficulties experienced in bringing NA9 to stable running. The subsidiary argument was made that we understood the spin of the proton since the measured magnetic moments of the baryons agreed well with the predictions of the naïve quark model. Hence it was felt by the proposers of continuing with NA9/28 that the polarised structure functions should behave as expected. How wrong they would prove to be!

The difficulty with continuing NA9/28 was that preparations were beginning for the experiments at the SPS collider (see Appendix F) and for future experiments at the collider experiments at the Large Electron Positron (LEP) accelerator at CERN and the Hadron-Electron Ring

Accelerator (HERA) at DESY in Hamburg.. Effort for experiments like EMC was clearly going to be scarce after 1983. If the polarized target had been delayed by another year it was unlikely that there would have been the support and effort to complete the two year run needed to achieve the allotted beam time. In addition the data from NA9 were being used mainly to guide the quark fragmentation models. The uncertainty on these models was larger than the statistical uncertainties on the experimental data.

A compromise was reached (see Appendix G) whereby the polarized target would be installed during the winter shutdown of 1983–1984. The vertex detector and its equipment would be taken to the US laboratory (Fermilab) to be installed in the E665 muon scattering experiment. Those groups interested in continuing the studies with the vertex detector would then join the E665 experiment. The EMC lost several significant groups who followed the vertex detector to the USA e.g., the Munich group and sections of the Wuppertal and Freiburg groups. EMC also lost the DESY group which left to prepare experiments for the future HERA Collider at DESY in Hamburg. However, the loss was compensated by the Yale group (Vernon Hughes *et al.*) joining EMC for the studies of polarized structure functions and the Heidelberg group (Dietrich von Harrach *et al.*) who were interested in the nuclear studies. Hence EMC remained a viable collaboration with somewhat fewer members (about 120 physicists – see Appendix A for the list of contributing physicists and participating institutions).

To further the studies of the EMC effect, a remote controlled nuclear and deuterium target system was designed and built by the Oxford group. This was used to place nuclear targets into the beam for short periods of time. The targets were interchanged frequently to minimize systematic effects. This allowed ratios of cross-sections from different nuclear targets to be measured with small systematic errors. Events from these targets could be differentiated from those from the polarized target from the position of the beam vertex. The results from these measurements provided more accurate data on the EMC effect (see EMC publications 60 and 68).

6 The polarized target phase of EMC

The dismantling of the vertex detector and shipping to Fermilab [19], the installation of the polarized target and reconfiguration of the Forward Spectrometer were not straightforward tasks. CERN engineers said it would take 2–3 years to complete these tasks, years that the EMC did not have. Perhaps they were motivated by the scarcity of CERN effort due to construction of the LEP collider and the preparation of experiments for it.

The situation was rescued by an engineer from the Rutherford Appleton Laboratory (John Alner) who produced flow diagrams to show that the work could be done in the few months of the winter shutdown between the end of NA9 in late 1983 and the restart of fixed target experiments in early 1984. He arranged for workers to come in from the EMC institutions to implement his plans. This was successful and the conversion from vertex detector to Forward Spectrometer, with both polarized and nuclear targets in place, were ready to begin data taking in early 1984.The polarized target data were then taken in 1984 and the first half of 1985.

Many in the EMC wanted to go to a dedicated nuclear physics run after completion of polarized target data taking. The purpose of this was to study the EMC effect in more detail. A proposal was submitted to the SPSC for running with the polarized target replaced by a series of nuclear targets. This became known as the Addendum proposal. The proposal was accepted by the SPSC but with no extension of the continuation of the experiment beyond the end of 1985. These targets were installed and the polarized target removed during the long maintenance shutdown in 1985 allowing further beam time to be devoted to studies of deep inelastic scattering in nuclear targets. Perhaps it was a mistake to curtail the polarized target run in this way – but hindsight is a good teacher. However, it maintained a good spirit in the collaboration since many were more interested in the data from the nuclear than from the polarized target. This reflected the future for the EMC apparatus which would be taken over by people with a dedicated interest in the physics of the nucleus.

In the 1986 collaboration meeting in Oxford it was recognized for the first time that the polarized structure functions were not behaving as expected. The predictions of the quark model of the proton were different from those shown by the data. Furthermore, the Ellis-Jaffe sum rule [20], expected from this model appeared to be broken. And so began the second startling discovery by the EMC (the first being the EMC effect). The discovery was by serendipity since almost everyone expected the polarization measurements to follow the predictions of the quark model of the nucleon (as alluded to above). After nearly a year to check the result, a Physics Letter (EMC publication 59) was published in 1987 announcing the discovery with a longer paper in 1988 (see EMC publication 65 and Appendix H). The discovery became known as the spin crisis since it showed that at high 4-momentum transfers only a small fraction of the spin of the proton was carried by the valence quarks. This was contrary to expectation and created great interest among theoretical physicists. Many theoretical papers have been published on the effect and many further experiments have been made to measure and extend the knowledge of the effect.

Analysis of the EMC data continued for a few years after data taking ended. The final EMC paper was published in 1993.

7 Subsequent muon experiments at CERN

The muon beam and ex-EMC and BCDMS infrastructures are still in use at the time of writing (some 40 years after the days of this history). The apparatus is similar but has been extensively modified and modernized and the beam has been upgraded. After the EMC experiment finished taking data in 1985 a new collaboration was formed which became the New Muon Collaboration (or NMC). This collaboration continued to use the Forward Spectrometer for further studies of deep inelastic scattering in both free nucleons (hydrogen and deuterium) as well as an extensive range of nuclear targets to study the EMC effect. After NMC had finished data taking another new collaboration was formed to study the spin structure of the nucleon. This became known as the Spin Muon Collaboration (SMC).The SMC used both polarized protons and deuterons to compare the spin structure of the proton and neutron. Finally, the apparatus and infrastructure were taken over by the Common Muon and Proton Apparatus for Structure and Spectroscopy (COMPASS) Collaboration to continue both muon and hadron physics in the North Area beam line.

8 Conclusions

The EMC was one of the first large experimental particle physics collaborations. It published 70 papers (see EMC publication list) in refereed journals as well as many papers in conference proceedings and technical papers describing different features of the apparatus. In addition there were about 70 PhD theses and numerous other theses resulting from work on the experiment. It made two seminal discoveries as described above and numerous detailed discoveries and measurements described in the EMC publication list below. The EMC became a very productive collaboration which developed its leadership pattern (see Appendix I) and had a very good social atmosphere (see Appendix J).

Appendix A: Lists of Participating Physicists in the EMC collaboration

The tradition within the EMC was that only those people who could defend the physics of the experiment were included in the author list of its publications. Hence the engineers and technicians in the collaboration were not included. The collaboration owes a deep debt of gratitude to these unsung heroes who built new apparatus as required and kept the existing apparatus in good working order.

A.1 List of signatories of the White Book [12]

This is the first page of the EMC proposal CERN/SPSC/74-78 (the White Book) showing the people proposing to take part in the experiment.

The European Muon Collaboration

British Participants: R. Clifft, E. Gabathuler, H. Montgomery, P.R. Norton, J.C. Thompson (Daresbury Laboratory), T. Sloan (Lancaster Univ.), G.R. Court, R. Gamet, P. Hayman, J.R. Holt (Liverpool Univ.), W.S. Williams (Oxford Univ.), F. Combley (Sheffield Univ.) and F. Farley (R.M.C. Shrivenham).

CERN Participants: M. Borghini and J.H. Field.

French Participants: J.J. Aubert, C. Broll, X. de Bouard, G. Coignet, J. Favier, H. de Kerrett, L. Massonnet, H. Pessard, F. Vannucci and M. Vivargent (Institut de Physique Nucléaire, Orsay).

German Participants: H.J. Behrend, F.W. Brasse, W. Flauger, J. Gayler, V. Korbel*, A. Ladage, J. May, P. Söding (Deutsches Elektronen-Synchrotron, Hamburg), U. Hahn, K. Moser, K. Rith, E. Schlösser, H.E. Stier (Freiburg Univ.), O.C. Allkofer (Kiel Univ.), K.H. Becks, J. Drees, U. Opara and H. Wahlen (Wuppertal Univ.).

* Now at CERN.

Italian Participants: P. Dalpiaz, P.F. Dalpiaz, M.I. Ferrero and C. Franzinetti (Turin Univ.).

Contactman: E. Gabathuler - present address NP-Division, CERN.

A.2 Participating physicists in the first phase of the EMC experiment (NA2)

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A.3 Participating physicists in the NA9/NA28 Phase of the EMC experiment

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A.4 Participating physicists in the polarized target phase of the EMC experiment

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These lists are almost the complete list of physicists associated with each phase of the experiment. We apologize to anyone who has been missed.

Appendix B: Construction of the Forward Spectrometer

The constructors of the apparatus for the Forward Spectrometer were as follows: drift chambers W1, W2, W3 constructed by Freiburg University, W4, W5 constructed by DESY, W6, W7, and MWPC P1, P2, P3 by Rutherford Appleton Laboratory, scintillator trigger hodoscopes H1 by Kiel University, and H3, H4, and the veto V2 by Wuppertal University, calorimeter hodoscope H2 by Daresbury Laboratory and Lancaster University, halo veto scintillator hodoscopes by Oxford University, Cerenkov counter by LAPP (Annecy later Marseille) and Wuppertal, beam scintillator hodoscopes and proportional chambers also by LAPP, reconstruction software LAPP, CERN, and Torino, polarized target by Liverpool and CERN, trigger system and STAC target by DESY. The data acquisition system, beam, and the experimental hall infrastructure were built by CERN.

Appendix C: First Tuning of the Muon Beam (from Niels Doble)

After the 400 GeV/c primary proton beam had been commissioned onto the targets in the North Area, the muon beam (see Fig. C.1) was the first secondary beam to be set up starting 31 March 1978.

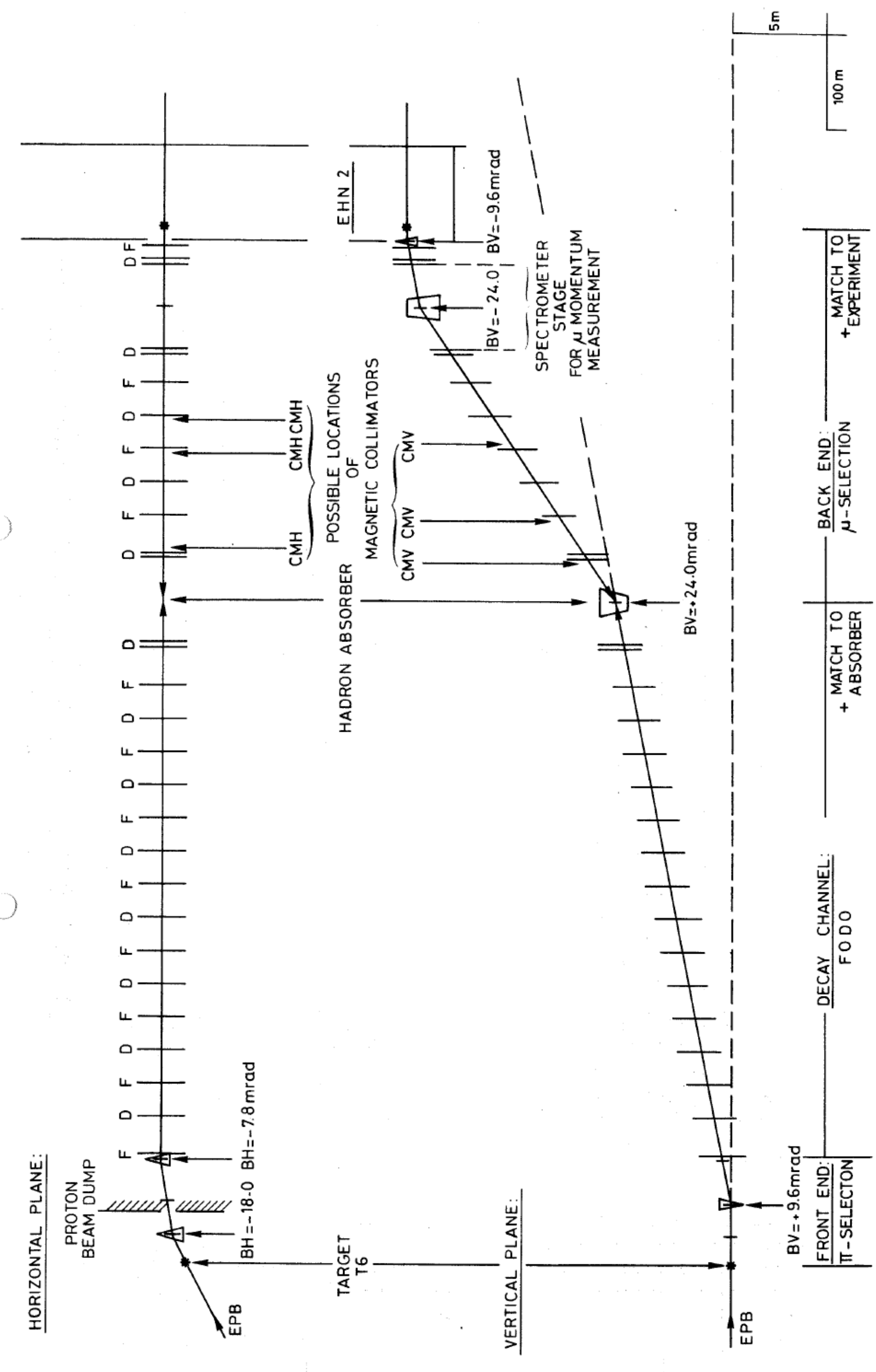

Fig. C.1: Schematic diagram of the beam. Triangles represent bending magnets, vertical lines represent quadrupole magnets (alternately focussing and defocussing) (picture taken from Ref. [14])

To avoid the high flux of protons present in a beam of positively charged hadrons, it was decided to start with a negatively charged beam of mainly π^- (at 220 GeV/c central momentum), leading to μ^- at momentum of 200 GeV/c. When the beam was switched on, profiles at multi-wire proportional chambers, located at the end of the pion decay channel and in the muon section, were immediately seen (see Fig. 2) and systematic tuning proceeded. However, after a few days, it was realized that the flux of muons counted by experiment NA2 (EMC) was higher than expected. The rate of π^- production (and hence of μ^- expected) was known to better than a factor of 2 from measurements at Fermi National Accelerator Laboratory (FNAL). It was decided to switch the beam polarity to π^+ to give μ^+. Lo and behold the flux was observed to LOWER by a factor of 3, suggesting that the charges transported by the beam were inverted! The position of impact of the primary proton beam on the beam dump following the production target and the momentum selection of the parent pion beam could be read on a series of thermocouples (called XBID from the French 'bidule'), which were mounted on the front face of the dump. And indeed, it was confirmed that the polarity of the $\pi \rightarrow \mu$ was inverted with respect to that intended.

The explanation was found to be a wrong calibration of the magnet polarity indicator, used to determine the polarity for a given sign of current in all the beam line magnets (dipoles and quadrupoles). Fortunately, the same instrument had been used to determine the polarity of ALL the secondary beam line magnets in the North Area. Otherwise we would have been faced with chaos!

Following this surprise, the steering and tuning proceeded according to plan for both positively and negatively charged beams at a variety of momenta ($\pm$220→200 GeV/c, $\pm$300→280 GeV/c, $\pm$140→120 GeV/c $\pi \rightarrow \mu$). A particularly intricate procedure concerned the optimization of the opening and inclination of the jaws of the 6 muon 'scraping' collimators installed along the beam. These consisted of 5 m long toroidally magnetized iron yokes, surrounding the beam, each fitted with a pair of lateral jaws, which could be adjusted remotely in both opening and inclination to embrace the beam envelope. Muons in the 'halo' accompanying the beam and entering the iron were thereby deflected outwards, away from the beam. In order to actuate each of the 4 motorized displacements of the jaws of each 'scraper', it was necessary first to cut the magnetizing current and subsequently to switch it back on and to wait for the eddy currents to decay before observing the rate in the 'halo counters'. This made halo-optimization a particularly lengthy undertaking!

Appendix D: Design and Construction of the Polarized Target (from Geoff Court)

These comments need to be seen in the context of the organization of the Liverpool EMC group. It involved G Court (GC), Peter J. Hayman (PJH), and Ray Gamet (RG) who were polarized target experts together with J.R. Holt FRS. GC had been asked by Erwin Gabathuler (EG) whether or not it was feasible to build a very large polarized proton target suitable for experiments in the proposed muon beam. Soon after this GC attended a meeting held at Daresbury Laboratory on 20 December 1972 arranged by EG. The others attending this meeting were the persons centred on Daresbury Laboratory who were interested in studying muon physics at CERN. The attendees were EG, GC, J. Bailey, P.R. Norton, T. Sloan, J.C. Thompson, and R.W. Clifft. The meeting agreed that a polarized target and a large solid angle detector to detect particles from muon interactions would be studied by this group of people.

GC, PJH, and RG concentrated on designing a realistic large volume polarized target. It rapidly became clear that the only practical solution for the proton polarizing magnetic field (2.5 T with uniformity of 1 in 10^5) was an independent superconducting solenoid providing only longitudinal proton polarization. It also became clear that, with the proposed muon beam, the requirements for good control of the systematic uncertainties in the asymmetry measurements and efficient use of the available beam time, that some form of two section target needed to be developed with opposite signs of polarization in each section (a technique which had probably not been used anywhere else before). The opposite signs of polarization would be exposed to the beam simultaneously.

The group at the time was fully committed to another experiment and so design effort was limited. The polarized target design in the White Book was therefore very preliminary. Once the White Book was submitted the design and development work on the polarized target was mainly continued by GC in collaboration with M. Borghini (MB, head of the CERN polarized target group). However, MB soon left the project, to be replaced by Tapio Niinikoski (TN).

Two separate funding agreements for the target were negotiated; one with the UK Science and Engineering Research Council (SERC) to fund the Liverpool work and one with CERN to fund the work at CERN.

The initial polarized target cell design was optimized for overall minimum cost and complexity given a cell of length 1 metre and a total diameter determined by the calculated beam profile (see figure D2.5 of the White Book [12]). Multiwire proportional chambers together with finger scintillation counters were initially proposed to track individual muons in time coincidence with an event in the main spectrometer to determine in which target section the event had occurred. Only when an attempt to write a specification for these detectors was it realized that there was an intrinsic problem which arose because the beam optimized for minimum size, as in the White Book design, was not a parallel beam. In fact, it had a waist at the target cell region. Hence the design in the White Book was replaced by the only realistic solution to this problem which was to use a longitudinally split (tandem split) target cell with opposite polarizations in each and a parallel muon beam. The event vertex position then would define from which section an event originated. It followed that a gap between the sections was needed to take account of the precision with which the event vertex could be reconstructed.

There was a further problem with the White Book design of the polarized target. Focussing the beam at the polarized target would have generated a muon beam which was too divergent to be useful to the BCDMS (NA4) experiment situated downstream of the EMC experiment. In this case the two experiments would not have been able to use the muon beam simultaneously. Hence the use of a parallel muon beam allowed more efficient use of the beam time.

After MB left the CERN polarized target group, the size of the group was reduced as CERN changed its priorities to running the accelerators in collider mode. This lack of resources led to delays in the design of the target. The Liverpool part of the target was shipped to CERN and the complete target was assembled in Hall 186 in the summer of 1979. The photograph in Fig. D.1 shows the assembly in Hall 186. The target was tested with butanol in one section and ammonia in the other section. This test confirmed that high values of the polarization were feasible and the ammonia (which is richer in free protons) was chosen as the target material. The reduced CERN support meant that Liverpool had to take over responsibility for the production of the required 2 litres of irradiated solid ammonia. It also became clear, at this time, that other necessary infrastructure would not be ready for the planned installation of the polarized target in the winter shutdown of 1980/81. A major problem was the supply of liquid helium. The above-mentioned tests were done with two 1000 litre helium transport dewar flasks which was not a realistic arrangement for the experiment due to the time and effort needed for dewar changes. The CERN management had not taken into account the relatively large liquid helium consumption by the target which would require an on-line liquefaction facility.

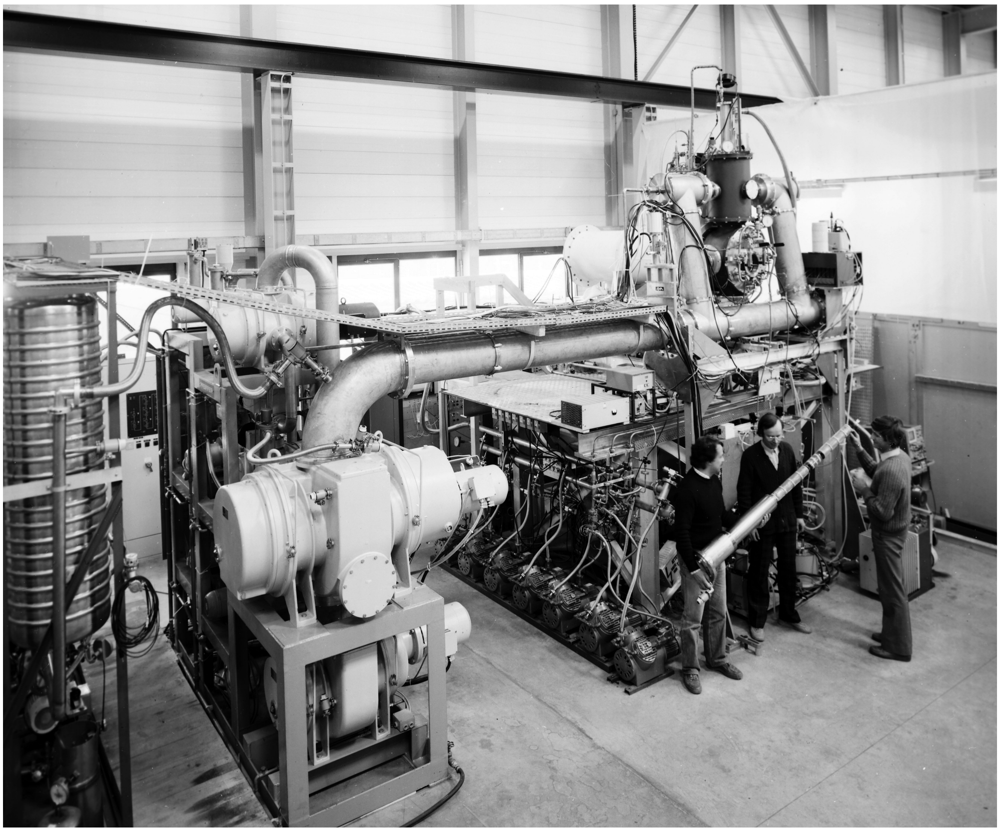

Fig. D.1: A photograph of the polarized target being assembled in building 186 at CERN. The target itself is being handled by the 3 people in the picture (centre Tapio Niniikowski, Michel Rieubland on the right, and one other) (image credit CERN, CERN-PHOTO-1826337).

Given the delays and the rather sceptical attitude of the collaboration to experiments with polarized protons, some discussion took place of abandoning the polarized target phase of the experiment. However, it was felt that a project which had cost so much in effort and money should not be abandoned. This was a fortunate decision given the seminal discovery of the spin crisis.

The superconducting vertex detector magnet had an on-line helium liquefaction system. The decision was taken to delay the polarized target phase of the experiment until after the vertex detector phase and use the vertex magnet on-line helium liquefier to furnish the liquid helium necessary for the polarized targets.

Appendix E: The 1982 Fire (from Hugh Montgomery)

The fire happened in the early morning of March 21, 1982, (Mont's birthday). At around 7 am, Tony Osborne called to say "Mont, I don't want to spend time talking, the experiment is on fire".

The fire damaged the epoxy resin in which the magnet coil was potted (see Fig. E.1). We were fortunate enough to find the mould for the coil on the Brown Boveri parking lot at Oerlikon (the original manufacturers). This saved the large amount of time which would have been necessary to make a new mould. The recovery plan required the coil to be newly potted at Oerlikon, transported back to CERN, and installed in the magnet. The damaged chambers also needed to be replaced. The procedure took about 3 months to complete and incurred some loss of beam time.

The fire had been caused by overheating of the leads to the electronics of the proportional chambers P1, P2, P3 inside the magnet volume. We were able to reproduce the fire on the bench! And had we been thinking, we had warnings. All the preceding afternoon, the P123 readout electronics repeatedly tripped through over-temperature! Being good physicists, we simply tried to reset and keep going. The photograph in Fig. E.1 shows the damage caused by the fire.

Fig. E.1: The effects of the fire inside the Forward Spectrometer magnet
(image credit CERN, CERN-PHOT0-1825941)

Appendix F: The Near Loss of the Iron Hadron Absorber to UA1 (from Hugh Montgomery)

Another story from Mont illustrates how fixed target experiments such as EMC had become lower in priority at CERN by 1982. CERN had become more interested in physics with colliding beams which yielded information on higher energy collisions. Preparations at CERN were advancing for running the SPS in collider mode, colliding protons and anti-proton beams, the so called $SP\bar{P}S$ mode. When Carlo Rubbia was looking to build the UA1 magnet, he considered requisitioning the magnetized iron hadron absorber used by the EMC which had been provided by CERN (see Figs. 4 and 7). This would have meant dismantling the downstream end of the Forward Spectrometer with consequential serious disruption to reassemble it with a non-magnetic absorber. The main reason to magnetize the iron in the muon absorber was to reduce hadron punch-through. EMC resisted the attempts of UA1 to use the EMC hadron absorber using the arguments for magnetizing the iron rehearsed in the early days. These eventually convinced CERN not to reallocate the EMC hadron absorber to UA1.

Appendix G: The Decision to End NA9 in 1983

The decision to change to polarised target running was made in a rather unusual Tuesday meeting (EMC had a group meeting every Tuesday at 2 PM). The proponents of polarized target running and those of NA9/28 were assembled and a compromise was reached after much discussion. The compromise was that those interested in the full coverage spectrometry of NA9 would take the EMC Vertex Detector to Fermilab and join the E665 experiment. Those interested in polarized target and studies of the EMC effect in nuclear targets would stay with the EMC at CERN. The changeover was scheduled for the end of 1983 data taking. The proponents of polarized target running were the Liverpool group (GRC, JRH, PJH, and RG), Erwin Gabathuler, Roger Clifft, Vernon Hughes from

Yale University, whose group had joined the collaboration specifically for such studies, and TS. This compromise was reached even though it fulfilled the wishes of a minority of the collaboration.

Appendix H: The Avoidance of Loss of Beam Time during the Polarized Target Experiment

During the run of the polarized target experiment, the experts wanted to invert the two halves of the polarization in the target twice per week to minimize the systematic errors due to small acceptance changes with time. This meant a loss of several hours of data taking at each polarization reversal. The compromise was that the polarizations were inverted only weekly on each Wednesday during the routine machine maintenance shut down, so that beam time was not lost. This led to headaches in assessing the systematic uncertainties due to time dependent acceptance changes. Such systematic uncertainties were proved to be small by comparing the measurements where the polarizations of the proton started the run in one sense (+-) with those which started the run with the polarizations in the opposite sense (-+). This allowed the time dependent shifts in apparatus efficiency to be studied reducing the systematic errors on the spin structure functions. These smaller systematic uncertainties were reported in the long paper on the polarization measurements published in Nuclear Physics B in 1988 (EMC publication 65).

Appendix I: Leadership and Process

The development of the EMC program involved the cooperation of several strong groups and their strong leaders. These people were leading lights in the pre-existing deep inelastic scattering experiments as well as division leaders at different laboratories throughout Europe. The establishment of the first and second spokespersons was accomplished using traditional methods. In 1974, Erwin Gabathuler emerged as the first spokesman with considerable support from CERN. His qualities being recognized more broadly, in 1978 Erwin was appointed CERN EP division leader (and later Research Director at CERN). Hans Stier (Freiburg) then became spokesperson of EMC. There was dissatisfaction within the collaboration about the process, which lacked transparency. The European Muon Collaboration was one of the first particle physics collaborations to exceed 100 physicists in number; this in itself demanded some formal process. After much discussion a more democratic procedure for electing future spokespersons was designed and adopted at the collaboration meeting at Wuppertal in 1979. To elect a new spokesperson, proposed names were deposited anonymously with an appointed person. All members of the collaboration were invited to contribute names. A committee then selected those names which appeared often. These names were written onto a ballot paper and an election was held using the two-envelope system to ensure a secret ballot.

Following this democratic procedure, Friedhelm Brasse was elected by the collaboration to be spokesperson in 1979. Subsequent spokespersons, Hugh Montgomery in 1981, and Terry Sloan in 1983 were elected using the same process.

Erwin Gabathuler's involvement with the EMC decreased with time after he became EP division leader. However, he maintained his interest in the experiment, for example participating in the weekly 'Tuesday Meetings', the recognized venue for decisions to be discussed. He was particularly interested in the personnel in the experiment and he would sometimes be seen in earnest conversations with individual colleagues. It became known that such discussions often involved quite intimate things such as personal problems or career directions. Perhaps as a result, he became known in the collaboration as Uncle.

There is evidence of some tension between Erwin Gabathuler and Friedhelm Brasse [21]. This tension was the effect of two strong men with slightly different views of the best way to do things. It would ease when the vertex detector was set up and mutual respect grew. Erwin and Friedhelm again worked together in the H1 Collaboration at DESY in the 1990s. When Friedhelm retired in 1994

Erwin presented him with a beautiful sculpture as a memento of their work together throughout the years.

Appendix J: The Social Atmosphere in the Collaboration

The EMC was in general a happy collaboration. There was a very good social atmosphere within it. The group had a secretariat who worked at the heart of the collaboration. There were frequent social events such as barbecues (see Fig J.1) and gatherings in restaurants. These contributed to a warm and friendly atmosphere which added much to the success of the collaboration.

Fig. J.1: A picture taken at the barbecue to mark the end of the EMC data taking in 1985. The author TS is side on to the camera in the foreground and the chief engineer (John Alner) is behind him also side on to the camera (image credit CERN, CERN-PHOTO-8508307).

The collaboration held 3-4 meetings per year when as many people as possible came together to discuss the issues and the physics progress. It was usual for one of these meetings in the summer to be hosted at one of the collaborating institutes, the remaining meetings taking place at CERN. In addition to this there would be more frequent meetings of the different analysis groups within the collaboration.

Acknowledgements

I should like to thank all my colleagues in the EMC, especially the founding fathers of the EMC the late Friedhelm Brasse [22] and the late Erwin Gabathuler FRS [23], for their support and hard work over the years recounted in this history. I am particularly indebted to Geoff Court, Niels Doble, Jörg Gayler, and Hugh Montgomeryfor for their provision of appendices and for a critical reading of the manuscript. I am also indebted to James Gillies and Jens Vigen for their assistance with the preparation of the manuscript and to Gerhard Mallot for his help with access to photographs.

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