C. RESEARCH AND DEVELOPMENT ON FUTURE ACCELERATORS : A NEUTRINO FACTORY COMPLEX

CONTENTS

C. RESEARCH AND DEVELOPMENT ON FUTURE ACCELERATORS : A NEUTRINO FACTORY COMPLEX

Personnel in 2000-2002
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Mauro Donega (Erasmus student from Università degli studi di Milano, September 2000- July 2001)
Maximilien Fechner (Intern from Ecole Normale Supérieure de Paris, January 2002 to September 2002)
Simone Gilardoni (Doctoral student at CERN since May 2000, 10% supported by Etat)
Juraj Krasnohorsky (Intern Université de Genève June-September 2002)
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+ technical team (electronics) from DPNC

Funding: FORCE subside, CHF 150 000.- for 2000-2001, 133 000- for 2001-2002; 100 000.- for 2002-2003, travel and operation budget from FNRS subside and DIP.

1. Introduction

It is by now well established that neutrinos have mass and that the three families mix. Coming after over thirty years of difficult experimentation using neutrinos from natural sources, this realization is probably the most important event in particle physics in the last ten years. It opens a field of research that could last several decades and culminate with the discovery of leptonic CP violation – a key ingredient in the understanding of the baryon-antibaryon asymmetry of the universe. This justifies an important investment in accelerator-based neutrino beams and experiments.

University of Geneva has been involved actively since the nomination of Prof. A. Blondel in early 2000 in the definition of this future program, with focus on those experiments which could first reveal the so far unobserved transitions from electron neutrinos and muon neutrinos at short wavelength, and on a longer term on the facilities needed to precisely measure mixing angles and mass differences, and establish CP violation. The ultimate tool in this endeavor is a neutrino factory based on a muon storage ring; this is a challenging novel accelerator for which a substantial R&D program is needed. Meanwhile, this research is likely to be dominated by large water Cherenkov detectors operating on low energy conventional or off-axis neutrino beams from pion decay. By end 2002, the program of research of a neutrino group at the

University of Geneva has been defined for several years, combining Neutrino Factory R&D (MICE) with participation in ongoing experiments (HARP, K2K).

The activities of the group in the years 2000-2002 have been as follows.

- Management of the ECFA sponsored study groups and of the European R&D (A. Blondel)
- Physics studies of neutrino oscillation experiments with superbeams and neutrino factory (A. Blondel, M. Campanelli, S. Gilardoni, M. Fechner, R. Piteira, G. Santin)
- R&D on target and pion collection (A. Blondel and S. Gilardoni)
- Participation in the construction, data taking, software and now analysis of the HARP experiment (A. Blondel, S. Borghi, M. Campanelli, C. Morone, G. Prior, G. Santin)
- Preparation of a muon ionization cooling experiment MICE, of a Letter of Intent and of a proposal. (A. Blondel, M. Campanelli, S. Gilardoni, J. Krasnohorsky, G. Santin). This proposal with A. Blondel as spokesperson is under review at the Rutherford Appleton Laboratory.
- The HARP activities lead naturally to a participation in the Japanese neutrino program, with the experiment K2K and possibly at a later stage in the J-PARC to SuperKamiokande experiment.

2. European R&D for neutrino factories.

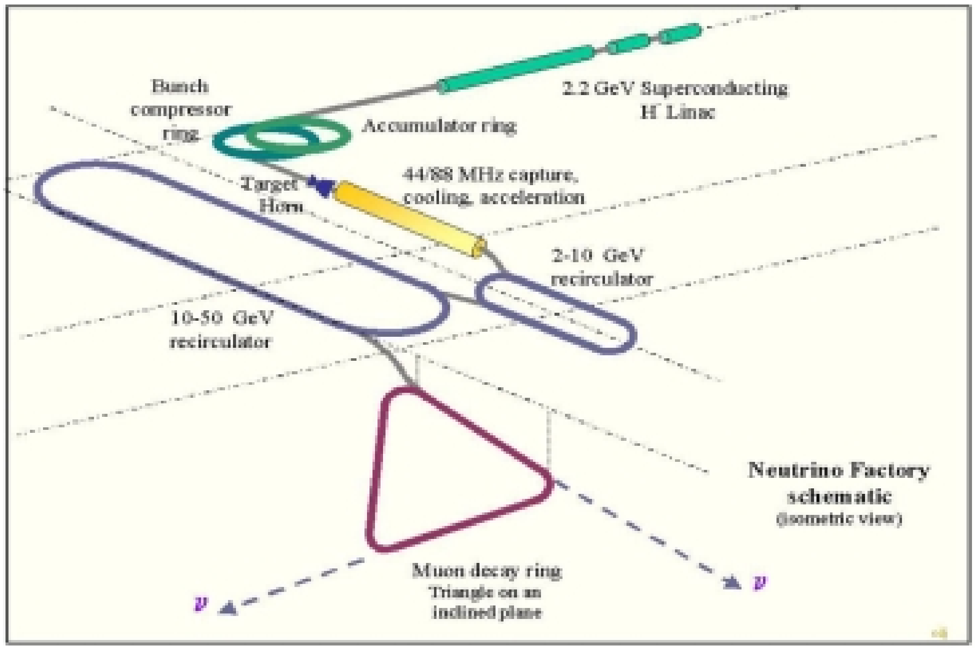


Figure 1: The CERN baseline scenario for a Neutrino Factory Complex

Following an encouraging prospective study in 1998 [1] a Neutrino Factory Working Group was created in 1999 by the CERN management. The neutrino factory was stated as one of the possible options for the future of CERN and the R&D for high intensity proton sources and neutrino factories explicitly described in the medium term plan of May 2001 [2]. This program made significant contributions leading to a CERN-baseline design for a Neutrino Factory [3], with original concepts for the pion collection with horns, for the cooling channel and for the decay ring of triangular shape (figure 1).

In view of the financial difficulties of CERN, this program that had started mid-1999 was cut in December 2001. This has made necessary a redistribution of the R&D efforts across European laboratories. The European Coordination and oversight group (EMCOG) was created in April 2002, under the chairmanship of Carlo Wyss, CERN director of accelerators. The group assembles representatives from the major European laboratories (RAL, PSI, Saclay, GSI, INFN Legnaro) and funding agencies (INFN, IN2P3) (A. Blondel is scientific secretary). The mandate of the group has been defined [4] and priorities set as follows, ordered from the source downstream.

1. High Intensity proton driver
2. target studies
3. Horn studies
4. Muon Ionization cooling experiment.

These four points require different skills and apply to different laboratories or universities. The EMCOG is presently actively working on setting up the collaborations and bids for placing request to the European Union under FP6 – Integrated Infrastructure Initiatives (I3) and under design studies. Encouraging results have been obtained, with RAL actively supporting the muon cooling experiment, and IN2P3 taking responsibility for the horn development.

3. Physics studies

3.1 Neutrino Factory physics studies

A. Blondel chairs the steering group of the ECFA sponsored studies of a European Neutrino Factory Complex. The University of Geneva group has participated extensively in the design of the accelerator [5] and in a comprehensive study of the physics capabilities of neutrino factories and other possible conventional neutrino beams. We have performed an evaluation of beam systematic errors at a neutrino factory, showing that, by a combination of the determination of the beam energy by spin precession of the muons in the storage ring [6] and by the measurement of the beam divergence [7], the neutrino flux could be controlled in such a machine with a precision of the order of one per mil or better [8]. Original work was done on the search for new physics signals in oscillations [9]. Mario Campanelli served as editor of the yellow report article [8] summarizing the work of the neutrino oscillations working group. The important gains for low energy muon physics that could be gained by inserting production targets in the accumulator ring were discussed in [10].

From these studies it appears clearly that a neutrino factory based on a muon storage ring is the ultimate tool for studies of neutrino oscillations [11]. Fig. 2 shows that it is the most sensitive accelerator for the search (and for the measurement) of the yet unknown mixing angle $\boldsymbol{\theta_{13}}$. Fig.3 shows the same virtue for the CP violating phase $\boldsymbol{\delta}$ in the neutrino mixing matrix. In either case the sensitivity exceeds that of possible alternatives by at least one order of magnitude. Although such a machine could be realized with existing technologies, much effort will be needed to reduce the cost and ascertain the performance. This is the motivation for a long term R&D such as the muon ionization cooling experiment MICE (see below)

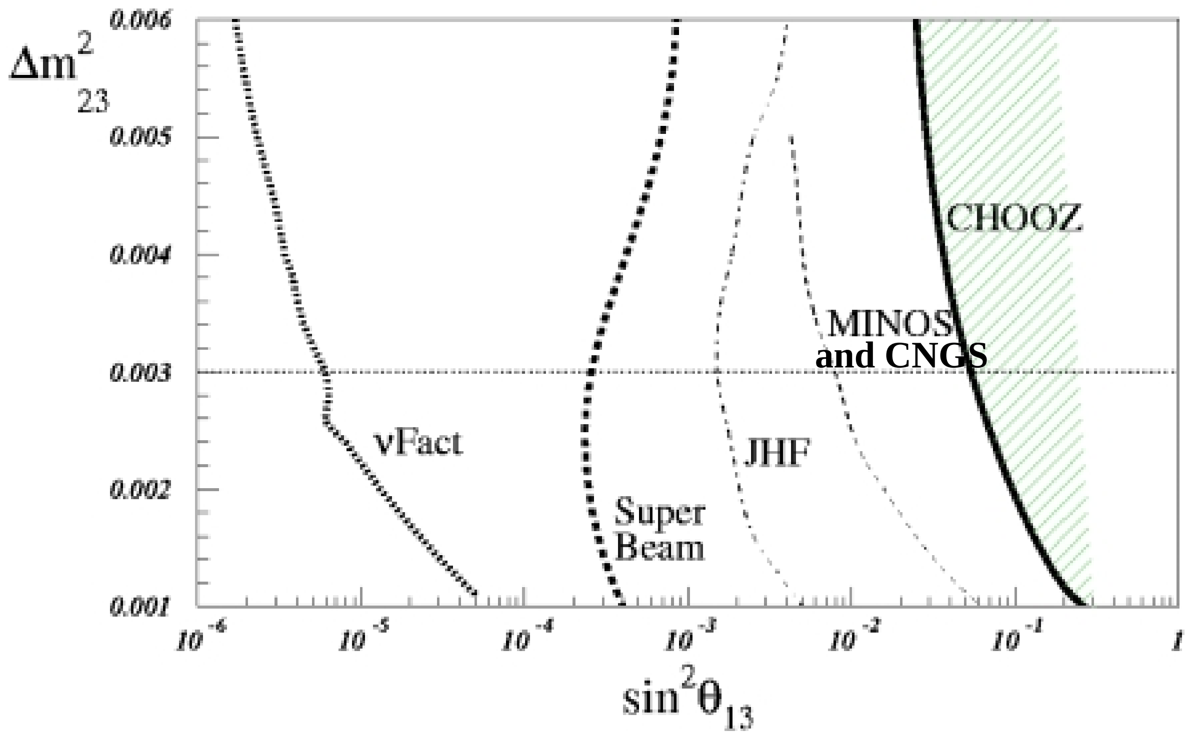


Figure 2 : Comparison of performance of various future neutrino facilities (from [13])

3.2 Super-beam and beta-beam

It was noted by our group that a first step towards a neutrino factory could be a low energy conventional neutrino beam exploiting the target and horn system [12] of the neutrino factory. The resulting neutrino beam could be used in an electron neutrino appearance experiment, for which a large water Cerenkov detector is the optimal tool. Our studies have shown that the neutrino beams that one could obtain from this machine are very competitive, surpassing the present limits on the $\upsilon_\mu \rightarrow \upsilon_e$ oscillations by two orders of magnitude, though falling short of what could be done with a neutrino factory by, also, two orders of magnitude. The sensitivity to CP violation was also studied and showed interesting sensitivity, provided a very large water Cerenkov detector (several hundred ktons of fiducial mass) could be fit at a distance of around 100 km from CERN. This is, incidentally, the approximate distance of the Fréjus tunnel. A workshop was organized in January 2002 at CERN [13] with the conclusion that this large detector would also be a very powerful tool to study other essential processes, such as proton decay and astrophysical sources of neutrinos (supernovae in particular). This interesting first step could become extremely promising with the advent of beta-beams (neutrinos from decay of radioactive isotopes), which have been proposed by Zucchelli [14]. The investigation of this possibility will be continued in a workshop that is organized in March 2003 at the occasion of the Moriond Conference. [15]

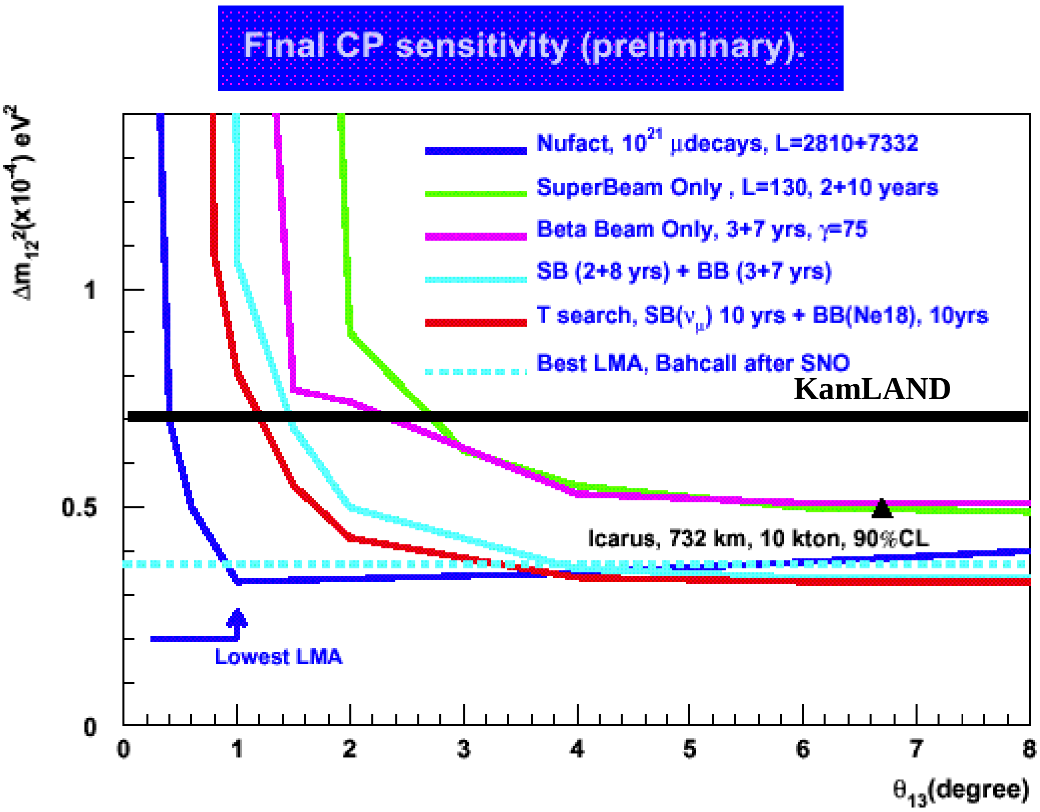


Figure 3 : Comparison of various facilities in their reach for CP violating effects in neutrino oscillations (from [8]).

Finally, we have shown [16] that the kinematic reconstruction of the low energy quasi elastic neutrino events such as $\nu_e N \rightarrow e^- N'$ could lead to sizeable improvements in the sensitivity to neutrino oscillation parameters (figure 4).

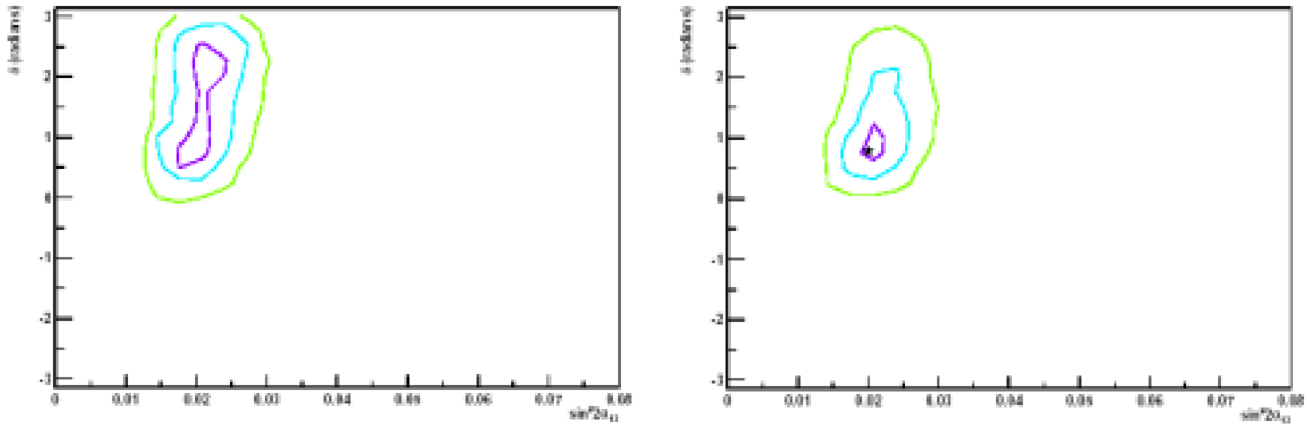


Figure 4 : precision on the angle θ_{13} and on the CP violating phase δ for a super beam experiment accumulating 200 kton-year of neutrino data at the CERN SPL and 2000 kton-year of antineutrino data. On the left: event counting only; on the right event counting and event by event neutrino energy reconstruction. [16]

4. Target and pion collection.

Simone Gilardoni has now become the recognized expert in the design and simulation of the pion production target, and in the magnetic horn collection system for Neutrino Factory and super-beam in Europe [17]. The baseline design of a horn for the neutrino factory is shown in Figure 5. This horn has been built and is being tested with low currents and low frequency to characterize the mechanical response of the horn. Ultimately high currents (up to 350 KA) and high frequency (up to 50 Hz) will be necessary. Although this program has been slowed down due to the cuts at CERN, the University of Geneva has helped by providing cash for small purchases, thus saving considerable time.

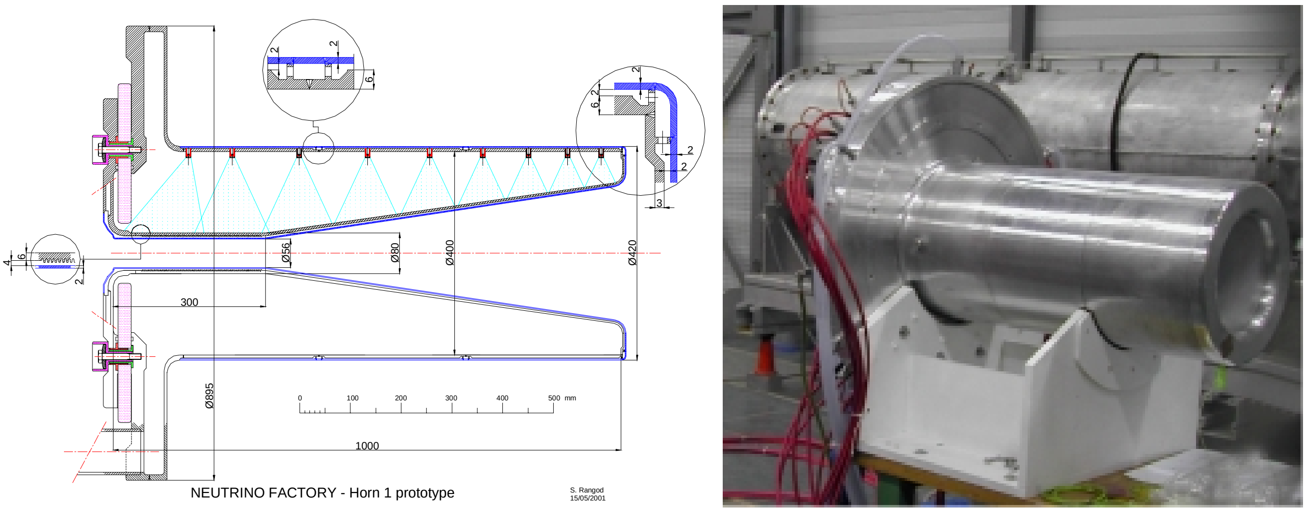


Figure 5 : Left: horn design for a neutrino factory or low energy high intensity neutrino beam;

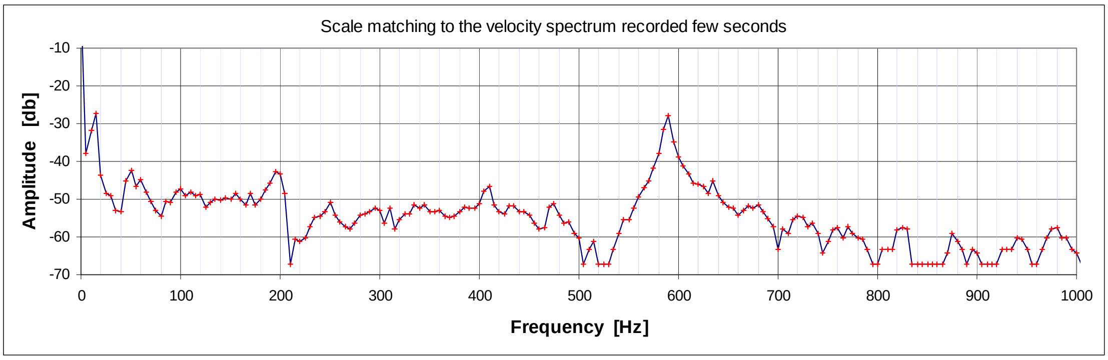


Figure 6 : Measurements of the horn vibration frequencies using a laser vibrometer.

The design of horns requires design of a power supply that delivers the highest possible current in the shortest possible time. A minimum of about 100 µs has been achieved for a current of 100 kA and with a repetition rate of 1 Hz so far. A serious difficulty with the CERN design is the fact that the accelerator, thereby the horn, has a high repetition rate of 50 Hz. It is crucial to verify that the 50 Hz will not resonate with one of the horn intrinsic frequencies. This has been test by measuring the vibration properties with either a microphone [18] or a laser vibrometer as in Figure 6.

A power supply of 300-400 kA at this repetition rate is a distant extrapolation from the present ones. The next steps should be to first reach higher current – a study is undertaken to see if the CNGS power supply could not be used – or higher repetition rate – for which one is considering using the MiniBoone 15 Hz power supply at Fermilab. In the end a larger program of R&D will be needed than what CERN is presently able to support. The good news is that the Laboratoire de l'Accélérateur Linéaire (LAL, Orsay IN2P3) has declared interest in pursuing and financing these studies.

Important work is taking place to understand how to optimize the horn design for the superbeam constraints. This has motivated the introduction of the double horn concept (Fig 7) which increases the flux by nearly a factor of 2. It is difficult to place a reflector in the passage of the beam because of the heavy radiation.

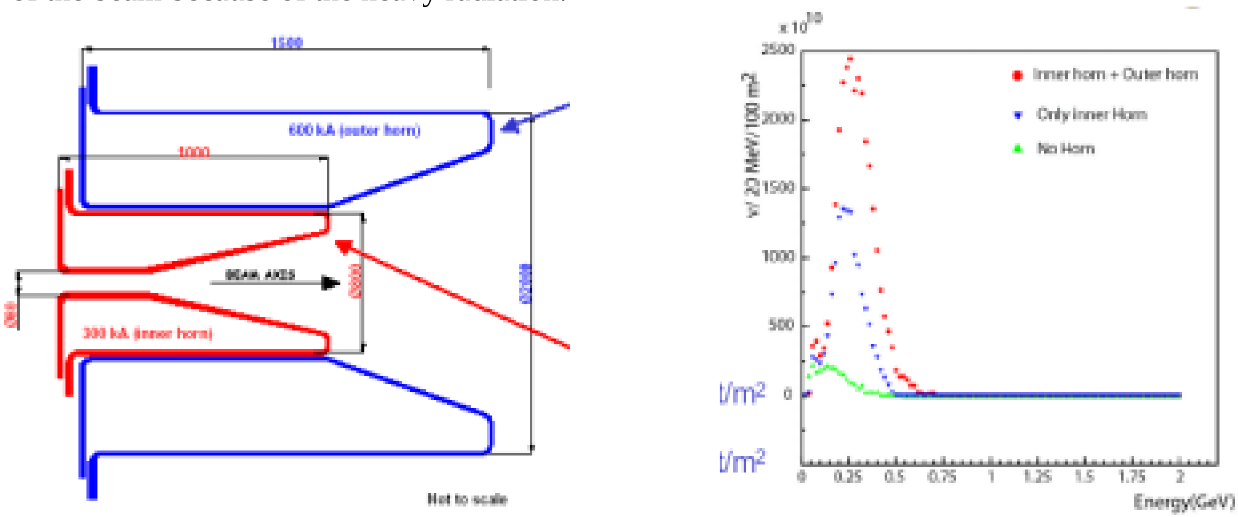


Figure 7 : Double horn concept and improvement in the flux for the low energy superbeam.

5. The pion production experiment HARP[19]

The physics objective of HARP is a systematic and precise study of hadron production for beam momenta between 2 and 15 GeV/c for target nuclei ranging from hydrogen to lead. Existing data in this energy range is usually old and spans over limited parts of phase space. The experiment was approved on 17 February 2000 and began to take data with a complete apparatus by August 15 2001. The data taken in 2002 represent a very extensive coverage of energies and targets, including the targets of the K2K neutrino beam and of the Mini-boone experiment at Fermilab. A summary can be found in table 1. In addition, data were taken with a water target and a beam momentum of 1.5 GeV/c, in order to verify the ratio of production of μ^+ to μ^-, which is a crucial ingredient for the analysis of the LSND data in the Los Alamos experiment.

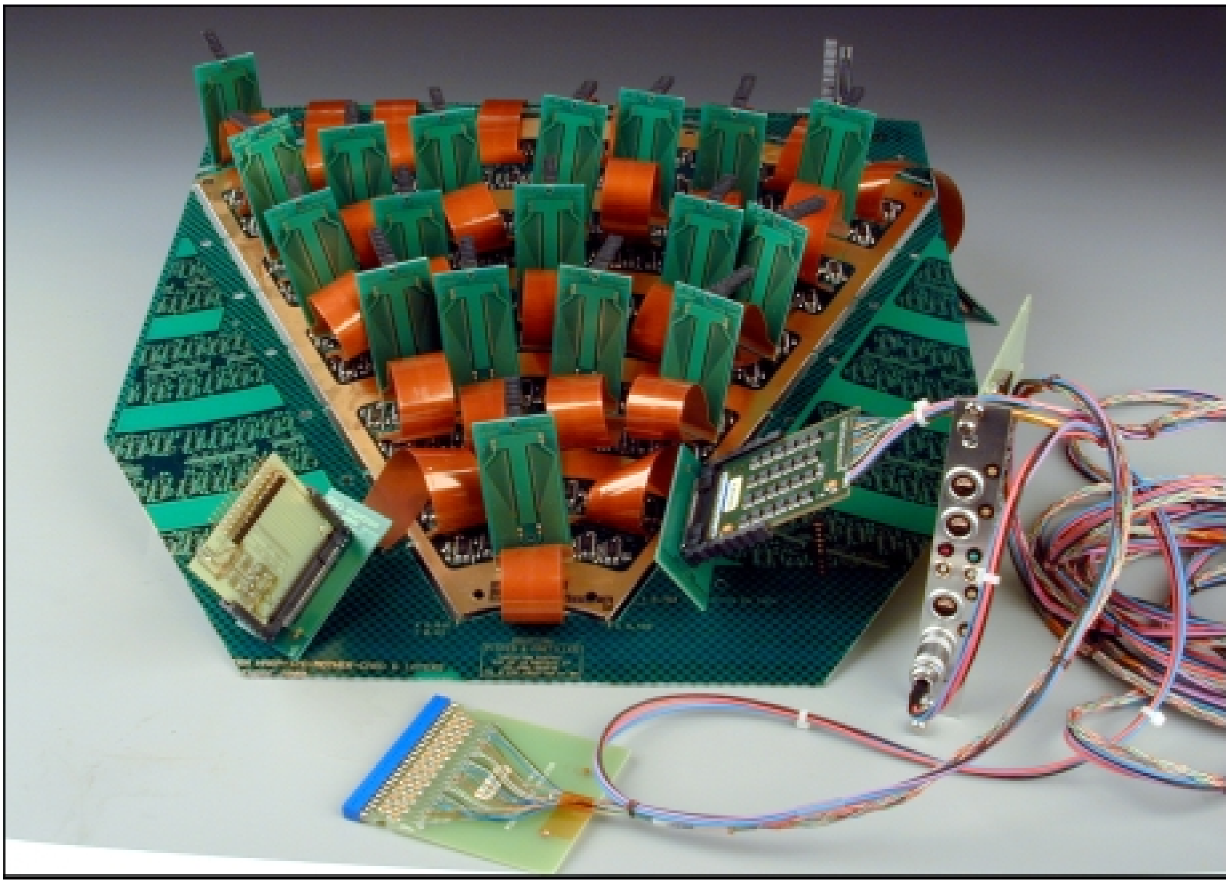
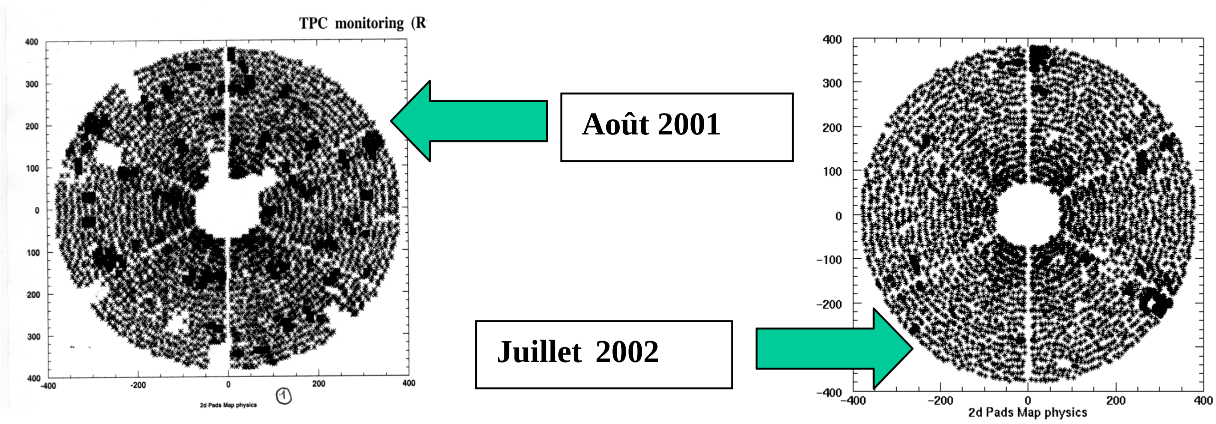


Figure 9: One of the motherboards of the TPC readout sector chambers, showing the "micro-flex" cables.

The major contribution of the Geneva group is in the HARP TPC [20]. The HARP detector was built largely from refurbished equipment but the TPC was entirely new. The Geneva group has contributed the largest part of the 4000 ADC channels thanks to the FORCE subside. We have been involved with the construction of the TPC readout and electronics, to which Silvia Borghi and Gersende Prior have remarkably contributed. The TPC was finished by July 2001. Cristina Morone has taken an important role in the data acquisition of the experiment, in particular for the TPC readout. During the shut-down 2001-2002 a considerable amount of activity was devoted to eliminating dead or inefficient channels in the TPC, with a resulting efficiency of better than 98% and a considerable reduction in the data volume. The work of G. Prior in particular has allowed the increase in data taken from 100 events per PS spill in 2001 to 500 events per PS spill in 2002.



In addition we assume responsibility for the TPC clustering and track reconstruction, with the work of Silvia Borghi and Cristina Morone. The picture of a HARP event with the reconstructed tracks can be seen in Fig. 8.

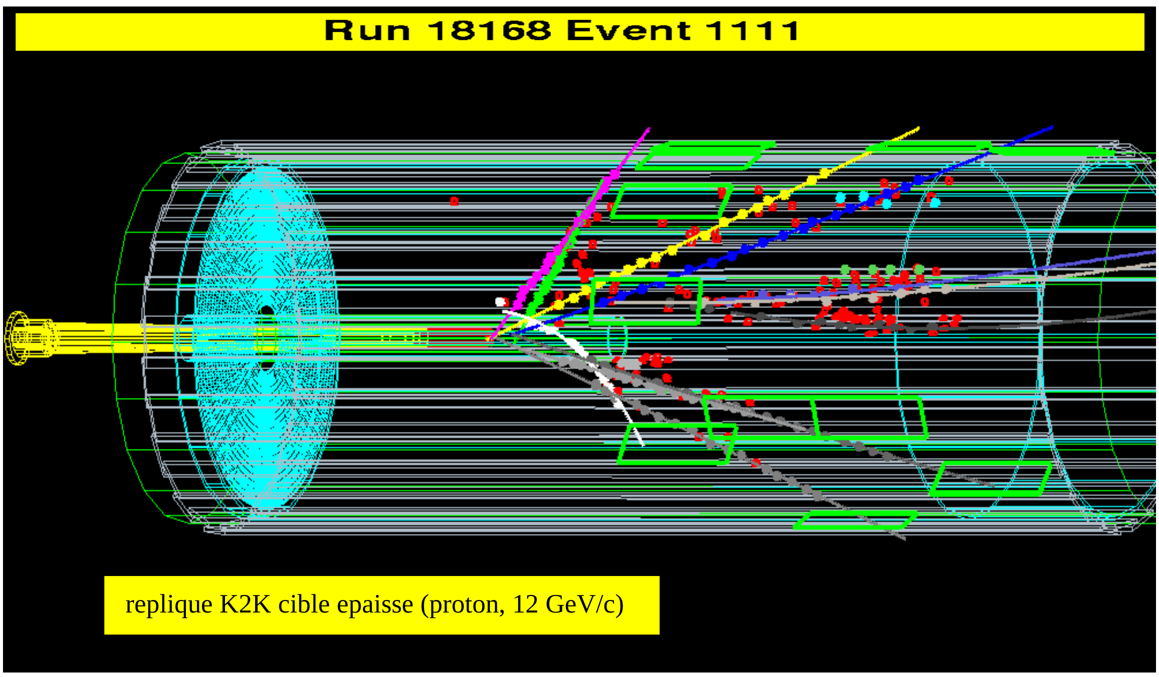


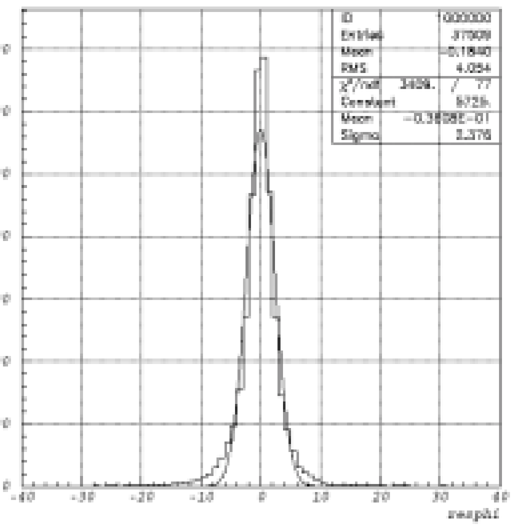
Figure 8 : 3D view of a 12 GeV/c proton interaction in the HARP TPC, showing the raw TPC hits and the reconstructed tracks.

Target	+3 GeV/c	+5 GeV/c	+8 GeV/c	+12 GeV/c	+15 GeV/c
Be 5%	1.54	1.95	2.23	0.63	0.91
empty	0.13	0.10	0.14	0.18	0.15
Be thick	1.16	1.09	1.09	1.81	0.74
C 5%	1.63	3.37	2.27	2.15	0.81
empty	0.37	-	0.32	0.23	0.14
C thick	1.11	1.12	1.01	0.66	0.96
Al 5%	1.93	2.07	2.22	0.73	0.71
empty	0.12	0.20	0.16	0.14	0.14
Al thick	1.34	1.29	1.27	1.15	0.70
Cu 5%	1.16	2.49	2.95	0.85	0.65
empty	0.16	0.14	0.14	0.14	0.15
Cu thick	1.12	1.58	1.40	1.93	0.83
Sn 5%	1.87	3.25	3.15	2.05	0.63
empty	0.21	0.14	0.17	0.14	0.15
Ta 5%	2.62	2.38	2.33	1.04	0.62
empty	0.15	0.10	0.20	0.15	0.08
Ta thick	1.01	1.33	1.49	1.56	0.61
Pb 5%	2.49	3.41	3.32	0.72	0.64
empty	0.10	0.10	0.16	0.08	0.09
Pb thick	0.76	1.26	0.98	1.12	1.10
Target	-3 GeV/c	-5 GeV/c	-8 GeV/c	-12 GeV/c	-15 GeV/c
Be 5%	2.33	1.39	1.76	1.21	0.85
empty	0.17	-	0.05	0.06	0.04
C 5%	2.26	1.81	1.63	0.74	0.62
empty	0.24	0.10	0.07	-	0.05
Al 5%	2.17	1.11	1.38	0.75	0.62
empty	-	-	0.7	0.09	0.05
Cu 5%	3.20	1.23	2.28	0.85	1.06
empty	0.08	0.24	-		0.03
Sn 5%	2.08	1.82	1.58	1.35	0.27
empty	-	-	0.07	0.08	-
Ta 5%	1.66	1.60	1.38	1.03	0.40
empty	0.25	-	0.07	0..08	-
Pb 5%	1.54	2.33	1.65	1.92	1.08
empty	0.11	-	0.10	0.06	0.04

Special Targets	
K2K at 12.9GeV /c	thin: 3.4 , medium: 3.1, replica: 3.67
MiniBoone Be at 8.9 GeV /c	thin:7.3 , medium: 5.17, thick: 2.84 replica: 4.05
Cu "skew" at 12 GeV /c	1.71M
Cu "button" at 15 GeV /c	0.24M

Table 1: data taken by the HARP experiment in 2002.

The performance of the TPC was assessed (S. Borghi, C. Morone) using cosmic rays, for which the track is separated in two halves by the inner tube dead shadow, allowing evaluation of the spatial resolution of the TPC and its performance for angle and in momentum reconstruction. The distribution of r-phi residuals shown in figure 9 indicates a resolution of 2.4 mm, which is a factor about 5 worse than expected. This was traced back to a faulty design in the CERN-made pre-amplifier circuits and has triggered a campaign of measurements to determine a cross-talk map to be corrected for offline. (G. Prior, S. Borghi). Presently the transverse momentum resolution is limited to about 20% at 200 MeV/c transverse momentum. Clearly the extraction of meaningful physics results will await correction for this effect.



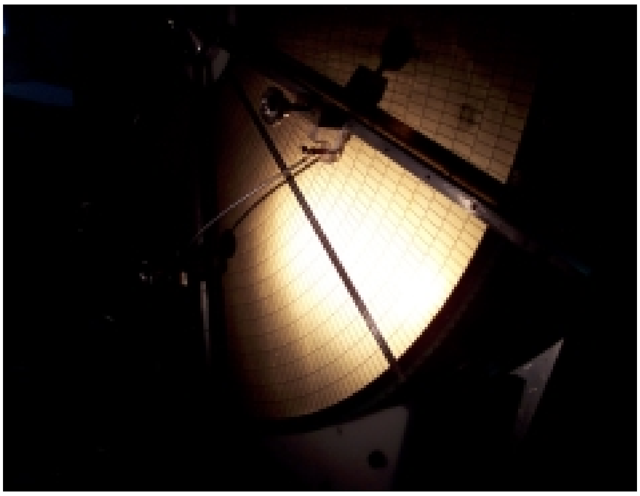


Figure 9 : left distribution of residuals in the HARP TPC; right: the test bench where the measurements of the cross-talk between channels are being performed.

Future plans for the work in HARP involve the measurement of particle production with the K2K targets, for which the connection between tracks in the forward direction and tracks in the TPC has to be developed This should be the subject of the thesis of Silvia Borghi. The other topic for which data are badly needed is the issue of strange particle production by low energy protons. Reconstruction of primary and secondary vertex, and V0 reconstruction, should be the thesis subject of Gersende Prior.

Data taken with HARP are extremely valuable for many applications. They have allowed us to win a contract with a European Space Agency for implementation of hadronic cross-sections in GEANT4, allowing us to support visiting professor Vladimir Grichine for 2003.

6. International Muon Ionization cooling experiment (MICE)

Cooling is an important component of a Neutrino Factory, both in performance and cost. The group is participant in the International Muon Cooling Experiment, the success of which is a crucial milestone in the demonstration of feasibility of a neutrino factory. Alain Blondel initiated the concept of the experiment [21], and was asked to convene the steering group in charge of setting up an international collaboration and acts now as European spokesperson of the collaboration.

The basic aims of the experiment [22] and a baseline scenario were defined and a letter of Intent submitted to the Paul Scherrer Institute (PSI) and to the Rutherford Appleton Laboratory. A total of 140 authors and 40 institutes, including several teams from large laboratories around the world (Fermilab, CERN, Brookhaven, Berkeley, Legnaro and RAL) are participating in this effort. The directors of RAL and PSI agreed to collaborate on this experiment, PSI providing a beam solenoid to allow RAL to provide a high quality muon beam for the experiment.

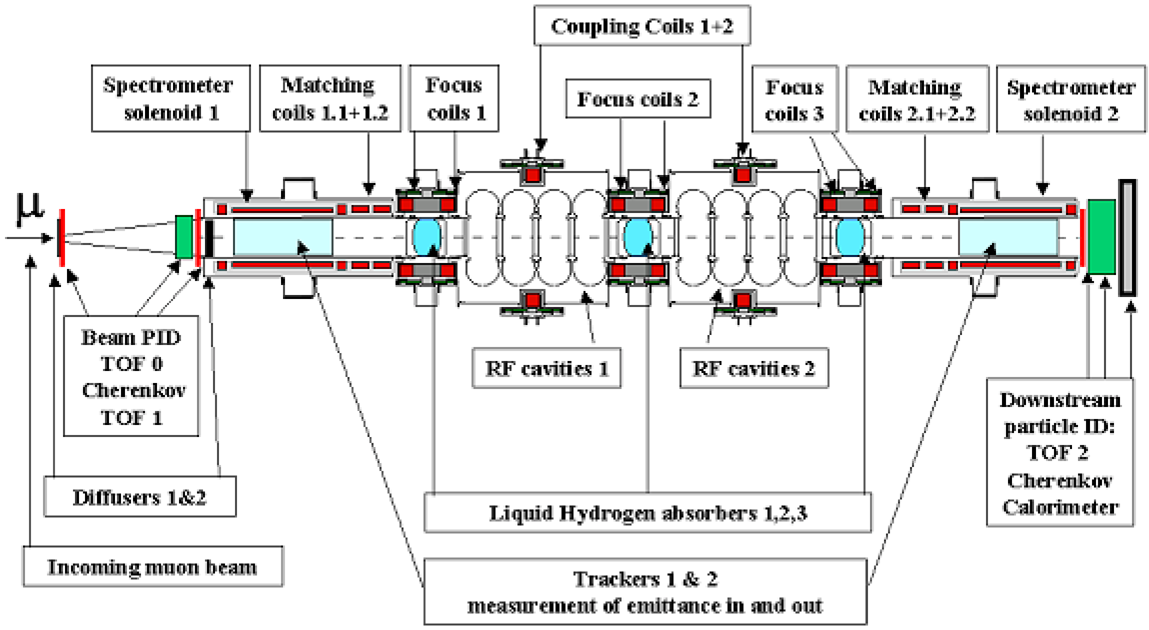


Figure 10 : layout of MICE, the International muon ionization cooling experiment.

Following the encouraging review by a panel of experts from PPARC and CCLRC (RAL) [23], a proposal [24] was submitted 10 January 2003 and is presently under review.

The central piece of the MICE experiment consists of a section of a cooling channel that was engineered in the context of the US study II [25]. This design was shown to work on simulations, being part of a global Neutrino Factory design that would provide 10^{21} muons injected in the storage ring per year. The aim of the experiment is first of all to show that this can be built in compliance with both the physics requirements and the safety and engineering constraints. The second aim is to place this section of cooling in a muon beam, and show that it cools. The experiment is designed to allow a number of beam conditions, magnetic configurations and absorbers to be tested, so as to understand a number of subtle aspects of the cooling process.

The difficulty is immediately that an affordable section of cooling channel only cools the beam by roughly 10%, while standard beam emittance measurements are of a precision of 10% at best. This leads to the concept of a single particle experiment, where the beam is characterized by measuring one muon at a time. The contribution of the University of Geneva group has been to propose the basic principles and configuration of the two spectrometers that are situated on both sides of the cooling section to measure the properties of the incoming and outgoing muons. The solenoid geometry is rather uncommon but it is the only one that allows detectors of reasonable size to measure the properties of a beam of very large emittance. (around 6000 π mm mrad). The system is completed upstream by a set of TOF counters to measure the time coordinate (with respect to the RF voltage), and identify the incoming particle as muon, and downstream by a system of particle identification to reject events in which a muon would have decayed into an electron.

Key issues for the experiment are i) the potentially heavy background of electromagnetic radiation from the RF cavities into the spectrometers and ii) the safety issues. The specific contribution of the Geneva group has been to propose, together with our former colleagues of HARP, a TPC read out with GEM chambers (TPG) [26]. This is an attractive possibility since it would allow to recuperate the electronics that we have invested for HARP, and a good part of the software experience. Such a TPC, filled with a light mixture (Helium based) could provide more than 100 points per track, ensuring good pattern recognition capability even in presence of background, and a resolution of a tenth of an MeV in transverse momentum. A test of the TPG readout scheme is being prepared for 2003 making use of the HARP solenoid, TPC field cage and read-out electronics. Simulations of the TPG constituted the internship work of Juraj Krasnohorsky. The principle of the TPG readout system is shown in figure 11 and 12.

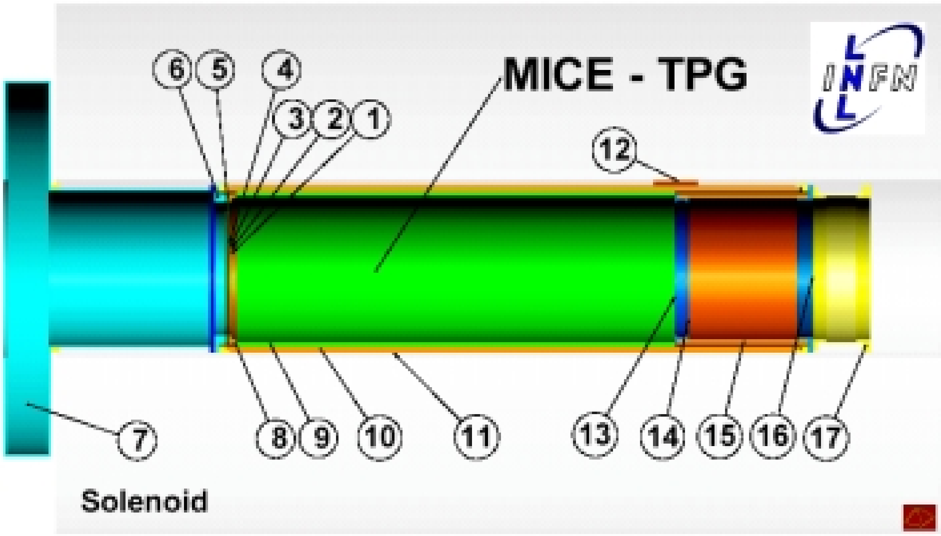


Figure 11 : MICE-TPG upstream detector. Muons enters from the left. 1: GEM-1 foil; 2: GEM-2 foil; 3: GEM-3 foil; 4: hexaboard; 5: Board (for hexaboard support, gas seal and signal connectors); 6: readout flange; 7: front-end electronics support and EM shield; 8: field cage termination; 9: field cage; 10: TPG isolating container; 11: TPG peripheral grounded shield; 12: HV inlet for drift electric field; 13: HV thin metallized foil cathode; 14: HV thin metallized foil gas seal; 15: HV foil support (insulating tube); 16: grounded thin foil seal; 17: TPG–LH2-absorber integration connection flange (schematic).

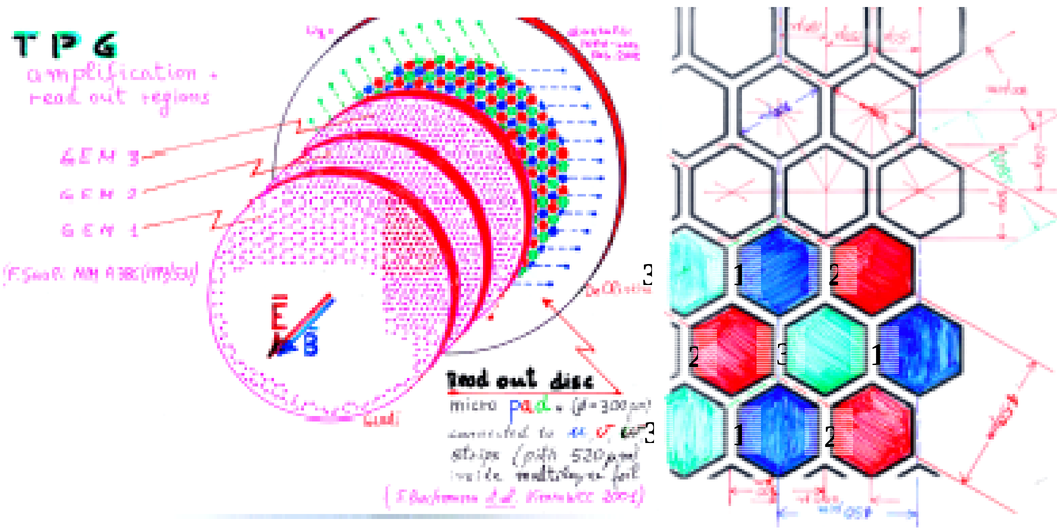


Figure 12 : TPG readout: left: the 3 GEM foils provide amplification onto the hexaboard. Right: the hexaboard with one third of the pads (blue) connected in strips at 30^{o}, one third at 150^{o}

Simulations of muons in the TPG have been performed in presence of a simulated background of x-rays. As can be seen in figure 13, the tracks remain very easy to reconstruct (and the resolution is not affected) even in the presence of several muons crossing the chamber at the same time, and of x-ray background.

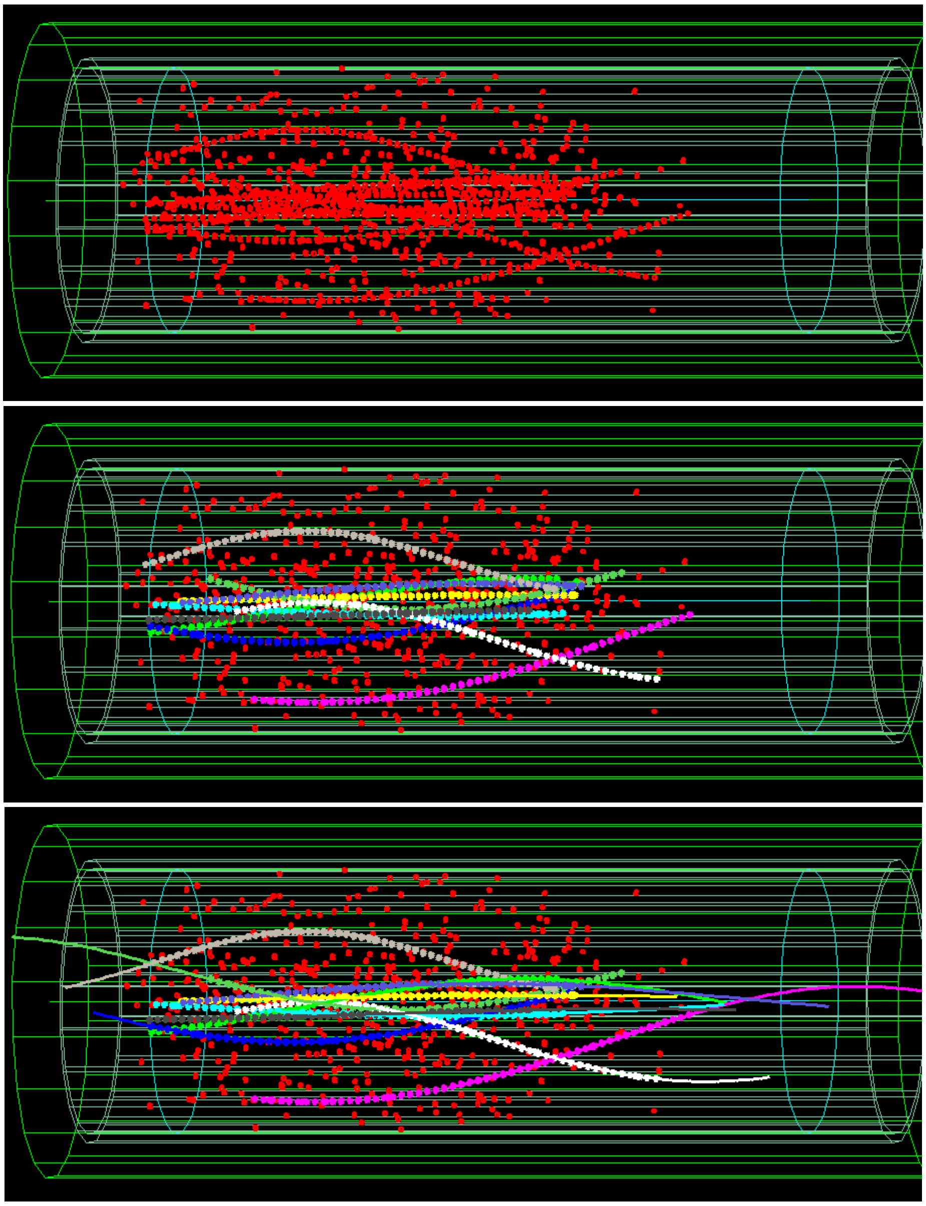


Figure 13: top: simulated track and noise hits in the TPG; middle: highlighted hits are those assigned by the pattern recognition to belong to the same track; bottom: track fitted on the selected hits.

The experiment has a development in time that can be envisaged as described in the scenario presented in Figure 14. First (step I) the beam can be tuned and characterized using a set of TOF and particle ID detectors. In step II the first spectrometer solenoid allows a first measurement of 6D emittance with high precision and comparison with the beam simulation. This should allow a systematic study of the tracker performance. Step III is fundamental for the understanding of a broad class of systematic errors in MICE. The two spectrometers work together without any cooling device in between and should measure the same emittance value (up to the small predicted bias due to scattering in the spectrometer material). Step IV, with one focusing pair between the two spectrometers, should give a first experience with the operation of the absorber and a precise understanding of energy loss and multiple scattering in it. Several experiments with varying beta-functions and momentum can be performed with observation of cooling in normalized emittance. Starting from step V, the real goal of MICE, which is to establish the performance of a realistic cooling channel, will be addressed. Only with step VI will the full power of the experiment be reached.

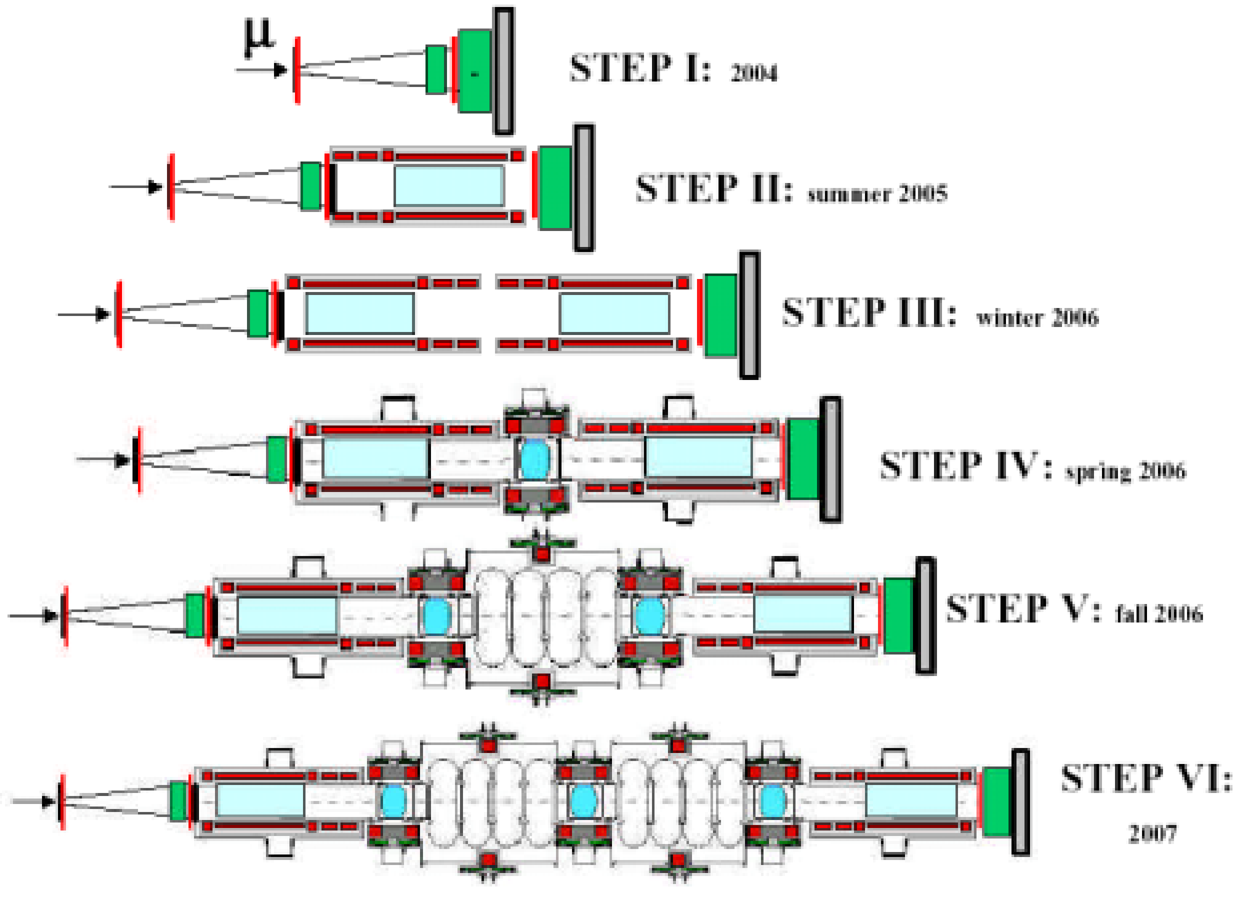


Figure 14 : Six possible steps in the development of MICE

7. Outlook: a neutrino physics group at the DPNC

The DPNC general meeting in July 2002 endorsed the continuation of neutrino physics activities. These will be focused on two complementary aspects:

7.1 Participation in the K2K experiment in Japan [27].

The opportunity to participate in a real long baseline experiment presently taking data presented itself as a combined consequence of i) our involvement in HARP where particle production in the K2K targets is being measured, and ii) the workshop on a large underground detector [13] in January 2002, where the long term value of large water Cherenkov detectors for neutrino physics, nucleon decay searches and astro-particle physics became apparent.

In the K2K experiment, a neutrino beam generated by 12 GeV/c protons at KEK points towards the super-Kamiokande detector 295 km away. The relatively low proton intensity available at KEK limits the sensitivity of the experiment, but it should nevertheless be able to verify and improve the determination of the mass difference $\Delta\ m^2_{13}$, which is so far only determined only by atmospheric neutrino experiments with a substantial systematic uncertainty on the neutrino flux. The knowledge from HARP data should help reduce the systematic uncertainty on the neutrino flux, which will soon become one of the limiting systematic errors on this measurement. The agreement with the K2K collaboration is that this will be the main part of our contribution to the experiment.

After a major accident in November 2001, the super-Kamiokande detector has been refurbished and is now taking data again. We will participate in the data taking starting in may 2003. It is expected that at least three DPNC theses will result from the participation to K2K, and University of Geneva has allocated a new post-doc position for this program. We will also follow possible developments for a higher intensity beam with the new accelerator in Japan, J-PARC, for which our expertise in horns for high intensity beams should be precious.

7.2 Accelerator R&D towards a European Neutrino Factory Complex

In spite of the spectacular success of the neutrino physics program in Japan, it is essential to pursue the successful undertakings in accelerator R&D in Europe towards a Neutrino Factory.. While it is probable that our involvement with horns will be reduced after Simone Gilardoni's thesis, some collaboration between LAL Orsay, CERN and ourselves will continue. Our efforts will concentrate on the MICE experiment. We have started to build a prototype GEM readout chamber in collaboration with Legnaro (U. Gastaldi), Bari (E. Radicioni) Napoli (G. Serracino) and CERN (F. Sauli). A program of tests of this device will be carried out in 2003 to ascertain its viability in the environment of MICE with a large flux of x-rays. This new technique can have many other applications such as detectors for future e^+e^- colliders. Participation in MICE installation and beam characterization will follow in 2004-2005 and should culminate with the first ever measurement of a beam emittance with a precision of 10^{-3}. This will constitute excellent diploma thesis topics and, funds permitting, PHD thesis topics.

A wider program of R&D towards a European Neutrino Factory Complex is foreseen, with the aim of being able to propose a major undertaking in Neutrino Physics by the time of LHC start up. A proposal requesting support from the European community is being prepared in the context of the ECFA-sponsored effort towards accelerator R&D in Europe.

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