Status of the SuperNEMO Design Study

The SuperNEMO-UK Collaboration

19 June 2006

1 Introduction

SuperNEMO is a next generation experiment to search for neutrinoless double beta decay as evidence for Majorana neutrino masses down to the level of 0.05 eV, the region favoured by oscillation experiments.

The idea of SuperNEMO is to follow the tried and tested technology of the previous NEMO experiments. The detector will have a thin $0\nu\beta\beta$ source foil surrounded by a tracking volume with Geiger cells to measure the trajectories of charged particles, a scintillator calorimeter to measure the energy of electrons and gammas and a magnetic field to help in the discrimination between electrons and positrons.

An important advantage of this type of experiment is that any isotope can be measured with the detector. The baseline choice is ^{82}Se and possibly ^{150}Nd if the enrichment proves to be feasible for this isotope. The detector will host 100-200 kg of isotope which represent more than an order of magnitude increase compared with NEMO-III.

Unlike NEMO-III, the SuperNEMO detector will have a planar highly modular geometry to make it easily expandable. The main challenges of SuperNEMO compared with NEMO-III is its size, more stringent requirements to the source radiopurity and better (about a factor of two) energy resolution of the scintillator calorimeter. The detector will be designed to reach a half-life sensitivity $(1-2)\times 10^{26}$ years which correspond to Majorana neutrino mass between 40 and 90 meV depending on the nuclear matrix element chosen.

Intensive R&D studies are currently underway in an international collaboration between the UK, France, Russia, Spain, the US, the Czech Republic and Japan. The UK and France are the major contributors to the project, important but smaller contributions are expected to come from other countries. The UK groups were the first to be awarded a three year design study grant in early 2006. In this document we report on the first phase of this work .

2 Organisation of the Collaboration

The funds awarded by PPARC triggered a similar award in France and applications for R&D contributions to SuperNEMO submitted by other collaborators (e.g. Spain) are awaiting decisions from their funding agencies.

The UK group comprises UCL and the University of Manchester. At the time of writing an application by a group from Imperial College (IC), led by Julia Sedgbeer, to join SuperNEMO is being considered by the PPRP. The IC proposal is to contribute in the area of simulations with possible future expansion in other areas. This will significantly augment the UK role in the collaboration.

In addition to the University groups, engineers and technicians from UCL's Mullard Space Science Laboratory (MSSL) play a major rôle within SuperNEMO. This contribution is essential given the significant technical challenges of the project.

The UK groups are responsible for crucial work packages in SuperNEMO: the Tracking Detector and Calibration. The main work is now concentrated on the Tracking Detector work package but we are also contributing to the Calorimeter, Physics Studies and Software work packages.

The project is in its very early stages (starting date is February 2006) and a significant fraction of this time had to be spent on organising the collaboration within the UK and internationally and on hiring qualified postdocs:

- The Manchester position was advertised in January and three candidates were interviewed in March. Irina Nasteva was identified as the best candidate. She has finished her thesis on ATLAS in June and has started to work on a 20 hour contract (not paid by the grant) for SuperNEMO on May 15. She still requires a work permit and will be paid full-time through the grant starting in August 2006.

- The UCL position was advertised in February and four candidates were interviewed in March − April. Zornitza Daraktchieva was identified as the best candidate and accepted the job offer. Dr Daraktchieva received her PhD in 2004 working on the MUNU reactor neutrino experiment which holds the best upper limit on the neutrino magnetic moment. Thus she has a very relevant experience in low background neutrino physics as well as an appropriate detector experience since MUNU is a tracking detector. Dr Daraktchieva is starting to work on the project in June.

- We have identified specific engineers at MSSL who will work on the project.

- We have identified a project manager, Mary Carter from MSSL, who will spend 50% of her time on the project management. Note that this time is bought from the money of the design study project.

- Both groups are also increasing their student effort on the project and are expected to take on more students in September 2006.

- The Manchester group has moved into their new lab space with a fully refurbished clean room in April/May 2006.

The main concern expressed by the PPRP expressed in its feedback to the SuperNEMO proposal was regarding the project management, organisational structure of the collaboration and coordination of the work between different countries. Consequently a lot of effort has been concentrated on these issues, specifically:

- A steering document and an organisational structure for the SuperNEMO collaboration was agreed upon at the NEMO Collaboration meeting at MSSL in April 2006. This document is based on a proposal by the UK groups and formalises the decision making process within the collaboration. The UK groups now hold the position of Deputy Spokesperson (Ruben Saakyan) of the SuperNEMO collaboration. The membership of the Institutional Board (IB) has been established and a Technical Coordinator of the experiment have been elected. A mechanism for IB and spokesman elections and the admission of new collaboration members has been implemented. The organisational chart of the collaboration is given in Appendix A.

- The managerial structure and the organisation of the work packages (WP) within of the international R&D effort is being finalised. The structure of the work packages and the responsible institutions are given in Appendix B. The main WP under the UK responsibility is the Tracker (Stefan Söldner-Rembold).

- We are also responsible for the Calibration work package and we are heavily involved in the Calorimeter WP. The latter is coordinated by French groups but the UK involvement is central to this effort since the work carried out at UCL demonstrated the feasibility of a $7-8\%$ energy resolution (FWHM at 1 MeV). This was crucial for the approval of the design study proposal. We are also participating in other work packages, mainly in the Physics Studies and Software work packages. The source WP is jointly coordinated by Russia and France.

In summary, we have made significant progress in establishing a formal structure which will ensure that the UK will play a leading rôle within the international SuperNEMO collaboration.

3 Work Packages and Deliverables

Work has started on the construction of the 9-cell prototype, designing the wiring robots and the characterisation of the photomultipliers. We have started procuring materials and constructing and designing various pieces of hardware under our responsibility.

Since the grant started in February 2006,the main deliverables which will have to be achieved by the end of this project in January 2009:

- R&D on critical components of the detector. Optimisation of the tracking detector and automatisation of wiring. Improving the energy resolution of the detector. Production and purity control of ultra clean $\beta\beta$ sources.

- Underground site selection (possible candidates are: New Frejus, Canfranc, LNGS, Boulby).

- Production of a full technical design report of the SuperNEMO detector.

Below a more detailed WBS and task sharing is described as well as present status of work with emphasis on the items under the UK responsibility.

3.1 WP1 Calorimeter

The UK responsibility in this work package (see Appendix B) is two-fold. We are responsible for R&D on Bicron plastic scintillators and for the characterisation of PMTs from ETL and Hamamatsu.

3.1.1 WP1 Status

A significant fraction of the scintillator work has been undertaken to demonstrate the feasibility of $7-8\%/\sqrt{E(\mathrm{MeV})}$ energy resolution at FWHM. This work led to the design study proposal approval and is described in detail in the original proposal.

Over the past few months (since February 2006) we conducted comparison studies of the ETL and Hamamatsu characteristics. The phototubes were purchased with the previous seed corn money and existing CAMAC/NIM electronics at UCL was used for the data acquisition system. Thus no equipment money from the grant has been spent for this work yet. We had to recommission the CAMAC/NIM DAQ due to the refurbishment work currently under way in UCL. We have studied the energy resolution characteristics and contributions of saturation effects to the response function. The saturation is an issue due to the high light levels in SuperNEMO scintillators (~ 1000 p.e./MeV) and high gains of the PMTs ($\sim 10^6$).

To carry our an adequate comparison between PMTs a small (2x2x2 cm^3) BC404 plastic scintillator was used. Such a small scintillator has a guaranteed good optical coupling to a PMT with any photocathode window shape. The setup was placed in a "dark" cupboard and schematically shown in Figure 1. A conversion electron source ^{207}Bi was used in the measurements.

The data were taken with and without a 2 mm Al disk placed between the source and the scintillator coupled to the PMT. The 2mm disk will completely stop all the electrons but will not affect photons from the source. By subtracting the data sets with the disk in and out we obtain the spectra of ^{207}Bi conversion electrons (482 keV and 976 keV). We then fit the high energy (976 keV) peak with three Gaussians taking into account K,L, and M conversion lines and obtain the energy resolution. The result of a typical fit is shown in Figure 2.

ETL and Hamamatsu showed similar energy resolutions at the low energy peak but at 976 keV both Hamamatsu 8" and 10" tubes showed a suspiciously good resolution of 5.5%. A detailed investigation showed that this was due to the saturation of Hamamatsu PMTs at high peak currents (~ 15 mA). No saturation was observed with ETL tubes at similar current. We have held a meeting with Hamamatsu engineers on 26 May and identified a solution $-$ a tapered voltage divider with a Zener diode at the first stages and an increased voltage between the last dynode and the anode to reduce the effect of the space charge. The order was placed and as soon as the divider arrives we will retest the Hamamatsu tubes.

We have also held talks with Hamamatsu regarding their new developments in high quantum efficiency PMTs. We are planning to buy one of their new products to conduct it thorough characterisation. Similar discussions are being planned with ETL.

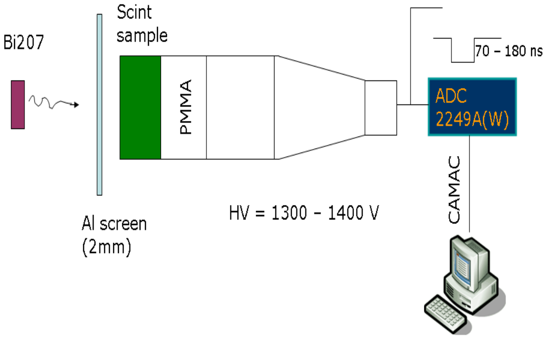

Figure 1: A highly schematic view of the setup used for the scintillator and PMT R&D.

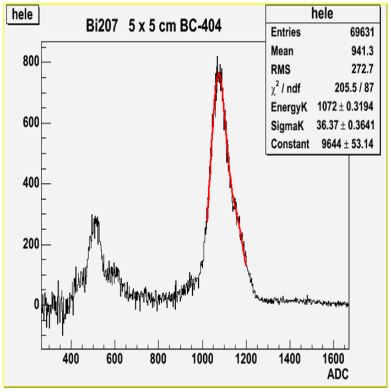

Figure 2: The 976 keV conversion electron peak fitted with three Gaussian corresponding to the K, L and M lines of the 1064 keV transition of ^{207}Bi.

We have started simulations of light propagation in the scintillator to optimise the light collection in the calorimeter. At the moment the work is in progress to reproduce the data from the test stand.

The future work and main milestones under this work package are summarised in the next sub-section.

3.1.2 WP1 Milestones

1 Development of VME-based DAQ for the calorimeter R&D and calibration studies (WP9) − December 2006

2 Scintillator block studies (size, wrapping, optical coupling etc). Comparison with other plastic scintillators results from collaborating groups. Baseline choice of the calorimeter material and geometry − February 2007

3 PMT characterisation: ETL and Hamamatsu. Comparison with other groups studies. Baseline choice of PMT. Written specifications for PMTs suitable for SuperNEMO − February 2007

4 Scintillator bar studies. Input from simulations. Optimisation of the resolution for scintillator bar readout − April 2007 (Depends on the approval of the Imperial bid)

5 Decision on the calorimeter layout (individual scintillator blocks or bars) − June 2007.

6 Construction of the calorimeter for 100+ cell prototype (TBD) − October 2007

3.2 WP2 Tracker

This is the main UK responsibility. The work in this WP can be broken down into three main categories.

- Development of the basic building block of the tracker (a cell), i.e. its length, wire diameter and material, gas composition etc.
- Development of the wiring robot which should completely automate the wiring procedure.
- Development of quick and reliable techniques for cell testing after manufacturing.

3.2.1 WP2 Status

Several aspects of the Tracker design have been addressed:

Mechanical Design Concept for Tracker Module

In conjunction with Jacques Forget (LAL) we have focused on a modular endcap design concept that decouples the production of cells from the final supermodule assembly (Figure 3). Individual cells are constructed using extruded endcap acetyl mouldings and wired by robot as single entities held under tension on a temporary support bar. Groups of individual cells can be tested and stored in simple boxes.

Individual cells (or subassemblies of cells) can then be shipped to a final assembly site where they are 'picked' from their transport frames and slid on to fixtures on the main support frame of the Super Module. The emphasis therefore switches to endcap design rather than frame design which becomes a relatively simple structural gas box.

Cell wiring: design aims to eliminate the need to thread wires, which is a major manual bottleneck to detector assembly. Cathode wires are formed in continuous loop round lugs on the plastic endcaps. Ultrasonic welding of small plastic clamps fix the wires in place. Similarly the anode wire is inserted sideways through a split in the cathode pickup rings.

Advantages of this design choice are:

- Cell construction can be done in conventional height clean rooms.
- Long tabletop operation rather than 5×4 m^2 high super modules
- The wiring robot becomes much simpler and the robot design less affected by changes to cell dimensions as a result of electrostatics studies.

Endcap Cell Mechanics and Wiring - 9-Cell prototypes

The infrastructure for the 9-cell prototypes has been set up by Ray Thompson in Manchester (Figure 4). Two clean 2×200 mm^2 diametre stainless steel test tanks have been assembled using vacuum components. A clean gas system mixing system with chillers for addition of alcohol and water is being commissioned. The first 9-cell module will be wired with an electrostatic cell similar to the existing NEMO-3 design, using conventional crimp pins for convenience. This will be used as a starting reference.

After some delays due to commissioning the new Manchester clean area, the cell will be wired in the next couple of weeks with the aim of first pulses by the end of July. Operating parameters will then be changed in the light of simulation, concentrating on gas and electrostatics.

The second module will be use to test a simplified version of the endcap concept (using CNC machined components rather than extruded). Drawings have recently been given to the Manchester workshop. We aim for a wired second module by end of September.

Wire length studies: a simple 4 m single cell (anode wire in a copper tube) will be setup by the end of September for propagation studies. The two test tanks can be reconfigured to form a single tank, eventually housing a rewired 9-cell 4 m prototype

Wiring Robot

The design of the cell layout requires close communication between the wiring robot work and tracker cell development. The collaboration has made a decision to opt for a full

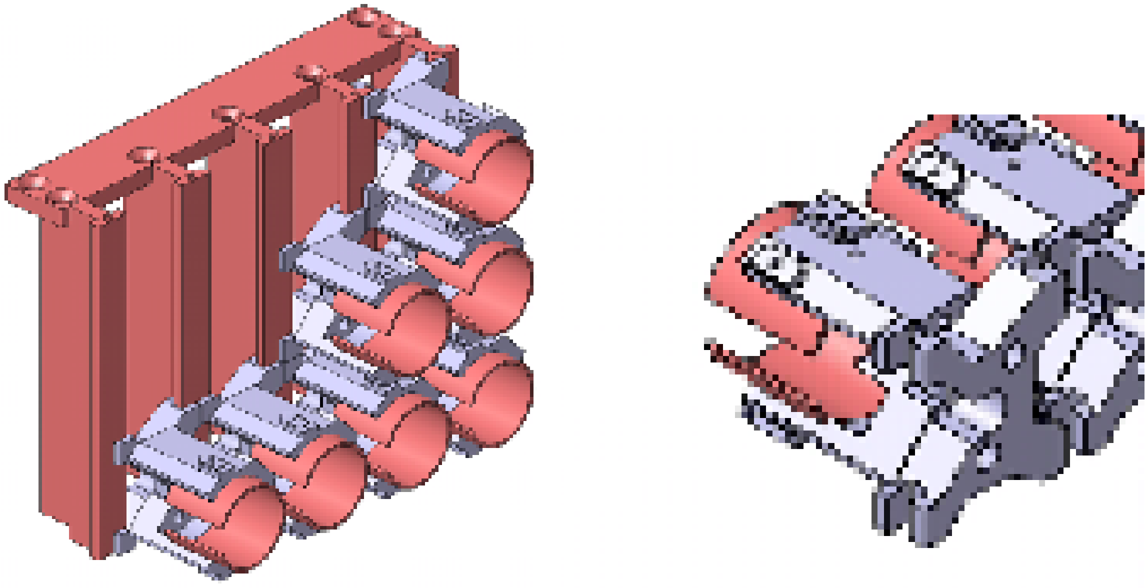

Figure 3: Endcap concept with cathode wire lugs and pick-up rings. The front view is shown on the left; the rear view on the right.

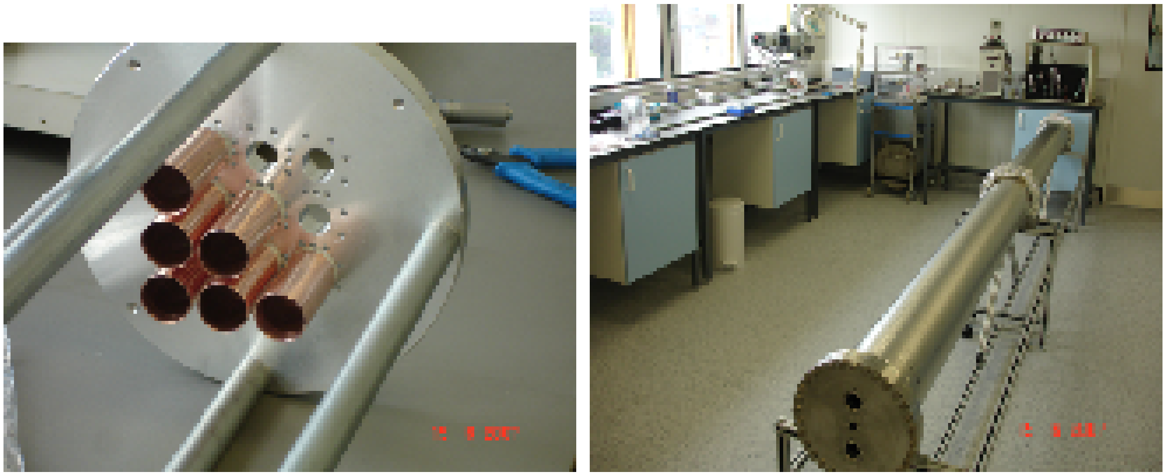

Figure 4: Cell endplate showing cathode pick-up rings (left) and joint 2-m long gas vessels (right) manufactured in Manchester in the new clean room.

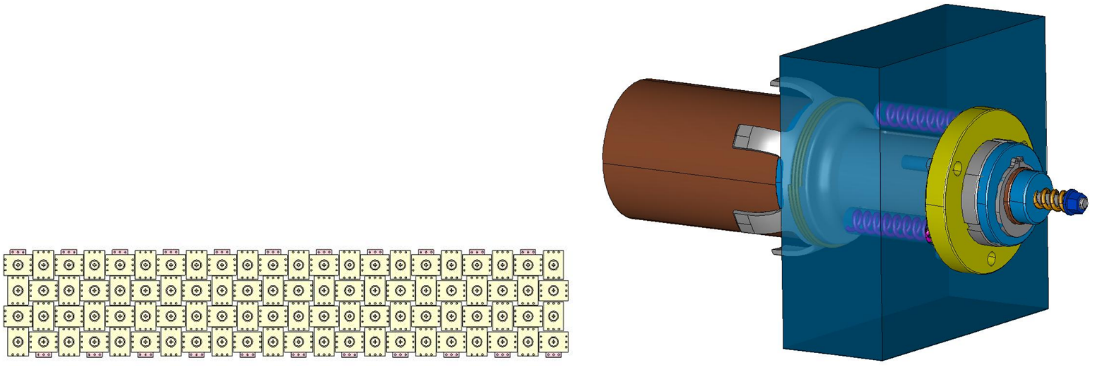

Figure 5: A possible 12-cahode cells layout with two building block units (left) and a possible end fitting design suitable for automating wiring.

automatization of the wiring procedure. As has been discussed above a full automatization is more feasible if individual cells are wired by the robot and then the cells are stacked up together to form a sub-module rather the wiring the sub-module as a whole.

The Tracker cell contains a single anode wire, a full complement of cathode wires (number TBD) and two end fittings. The building blocks are the wired units, which the wiring robot will produce. These will be stacked together to make up the Tracker cells and there may be more than one type of building block needed to complete the assembly. The number of types of building blocks needed to produce the Tracker cells should be kept to a minimum. The geometry should also be simple enough to make the stacking procedure of thousands of cells quick and easy.

Work has started in UCL and MSSL to identify possible layouts of the cell and the design of their building blocks and end fittings. One of the options of a 12-cathode cell layout and a design for the end fitting under consideration is shown in Figure 5.

9-cell Protoptype Simulations

After extensive discussions with our colleagues who designed and operated NEMO-3 we conclude that the main weakness of the NEMO-3 Geiger drift cell design is its narrow operating voltage range, between the start of efficient plasma propagation to both ends of the wire, and the onset of a continuous self-sustaining discharge. We aim to improve the operating range by use of small, 9-cell prototypes backed up by simulations. Irina Nasteva and Steve Snow at Manchester have therefore written simulations of the cell electrostatics in both Garfield and FlexPDE. An example of the outputs of these two programmes applied to our basic 9-cell prototype is shown in Figure 6. They clearly agree in this 2-dimensional case; our motivation for using FlexPDE is that it also works in 3D and so could be applied to the wire ends.

We have also simulated the gas used in NEMO-3 using Magboltz, which predicts the Townsend coefficient and attachment versus field shown in Figure 7. By combining the electrostatic and gas simulations we expect to develop a better understanding of the Geiger

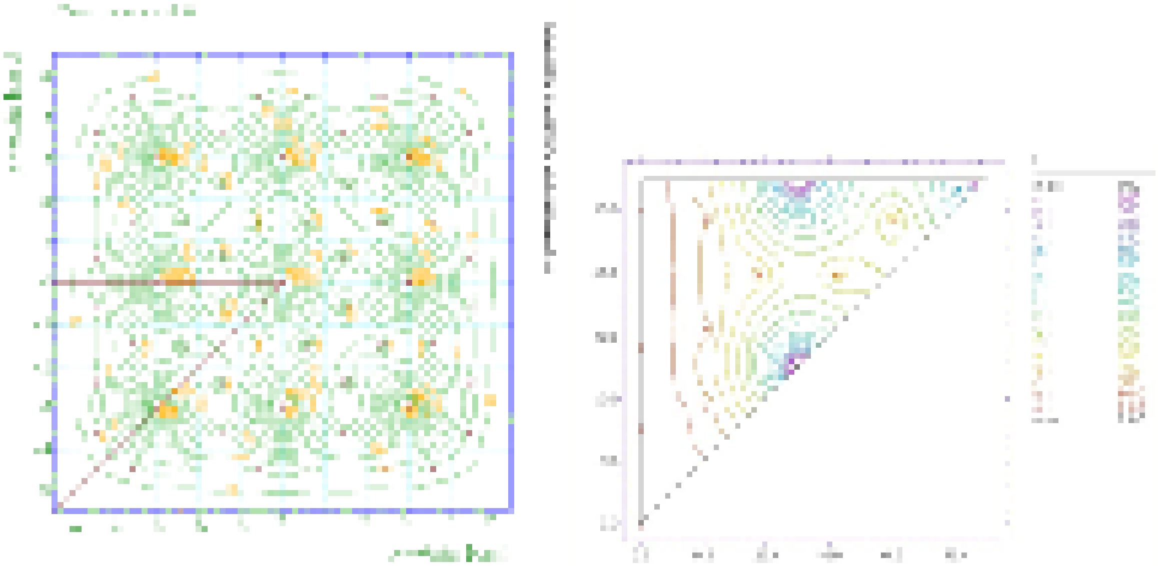

Figure 6: 9-cell prototype simulations using Garfield (left) and FlexPDE (right)

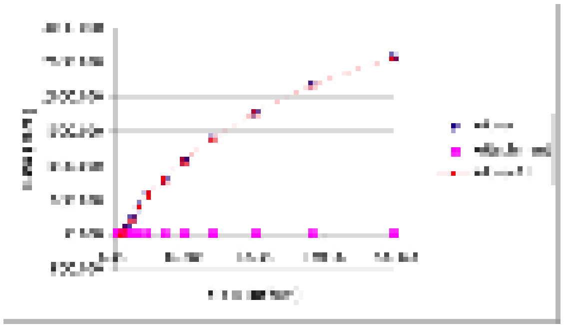

Figure 7: Attachment versus field strength.

plasma propagation and self-quenching mechanisms and thus improve the cell design (e.g., optimising wire and cell diametres)

3.2.2 WP2 Milestones

1. Gas system and rig for the 9-cell prototype – May 2006 (done)
2. Agreement of overall mechanical design concept for the Tracker (with LAL) – June 2006 (done)
3. Complete setup for first 9-cell prototype – August 2006
4. Test of Production of Forget Endcaps – September 2006
5. Complete setup for second 9-cell prototype – October 2006
6. Choice of basic SuperNEMO cell (wire material and geometry, number of cathode wires, gas composition etc) – February 2007
7. Cells layout feasible for automated wiring (Input from tests in Manchester and simulations) – Feb 2007
8. Design for the end fittings of each cell – Feb 2007
9. Final decision on technology for automated wiring including termination (e.g. ultrasonic welding) – April 2007
10. Design of 100+ cell prototype – March 2007
11. Construction of 100+cell prototype and possible integration with scintillator calorimeter – October 2007
12. Construction of wiring machine prototype – October 2007
13. Commissioning of 100+ cell prototype at MSSL – February 2008
14. Commissioning and tests of wiring machine – July 2008
15. Transportation of 100+ cell prototype to Canfranc (TBC) – April 2008
16. Commissioning of 100+ cell prototype at Canfranc – July 2008
17. Data taking with 100+ cell prototype – January 2009

3.3 WP9 Calibration

The calibration system in SuperNEMO will combine a light injection system (based on ultra-bright LEDs) and a radioactive source calibration. The system is conventional and in its main part will be designed and constructed at a later stage if the full SuperNEMO proposal is approved. However a conceptual design has to be done during the design study stage. Also we will have to provide a calibration system for the 100+ cell prototype which will be used to check the full calibration chain.

3.3.1 WP9 Milestones

1 Light injection calibration tests with LEDs and possibly lasers. Calibration on single photoelecton peak studies − December 2006

2 Choice of the radioactive calibration sources − March 2007

3 Conceptual calibration design − July 2007

4 Construction of calibration system for 100+ cell prototype − October 2007

5 Commissioning of calibration system for 100+ at MSSL − Feb 2008

6 Testing full calibration chain with 100+ at Canfranc − end 2008

3.4 WP7 Physics Analysis and Software

This activity is coordinated by Caen (France) but the UK is a key participant. The physics analysis and Monte Carlo simulations tools will be developed in parallel with the C++ based object oriented software framework. The collaboration greatly benefits from the existing NEMO3 software which include the most sophisticated to date event generator GENBB used to generate both double beta decay events and all possible radioactive backgrounds.

The existing simulation program, NEMOS with the embedded GENBB event generator is F77/GEANT3 based as is the NEMOR package which provides a basic reconstruction of simulated SuperNEMO data. The geometry of SuperNEMO is as yet defined individually by the user but normally within the existing software framework

The decision has been made that the SuperNEMO software framework will be entirely OO based on C++/ROOT. A C++/ROOT based reconstruction framework is being developed in UCL and Caen and this will provide the kernel for the final package. Work is in progress to produce a C++/GEANT4 based simulation package, SNSimPack (Caen, Orsay). There is an already available element to define the SuperNEMO detector configuration, with the option of default parameters (Caen). A SuperNEMO database is being planned (Caen, Dubna)

Within the UK the simulations and physics analysis tools development has started. The Manchester group have produced first simulations for the tracker design studies and first estimates of the SuperNEMO sensitivity and its dependence on the detector parameters based on NEMOS/NEMOR. A new algorithm with nested GEANT volumes was developed to optimize the hit simulation in the Tracker. Manchester is planning to upgrade this to C++/GEANT4.

The description of the main tasks in this package can be found in the original design study proposal. We would like to underline two simulation tasks here which formed the basis of the Imperial College bid to join SuperNEMO:

- to investigate an alternative to the baseline calorimeter design which could offer the advantages of a significantly reduced number of PMTs and a reduced overall detector size. This design envisages the use of scintillator bars read out at both ends instead of individual scintillator block readout in the baseline design.
- to study the site requirements for the experiment in terms of cosmic muon and neutron backgrounds.

A more detailed description of the proposed work can found in the Imperial proposal which is attached to this report. We would like to stress that this work is extremely important and also provide a great opportunity to augment the UK role in this physics simulations. As it stands now there is no manpower in the collaboration which can pick up these important tasks. The proposal was considered by PPRP on 6 June and the collaboration is awaiting the answer.

The simulations and software working group is being formed and will have to coordinate efforts of participants from all seven countries in SuperNEMO. There is a series of phone meetings planned in July and the group will meet in September to define the milestones and finalise the task sharing. The UK is already playing a key role in this activity and which will further be augmented if Imperial joins the collaboration.

4 Summary

The UCL and Manchester SuperNEMO group have successfully started an R&D programme for a future SuperNEMO detector. We have concentrated on improving project management within the UK and within the SuperNEMO collaboration. Both groups have hired new postdocs. The first milestones of the project have been successfully achieved.