Proposal for an IN2P3 contribution to the n2EDM project at PSI

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IN2P3 Scientific Council
(23/10/2013)

1 Introduction

The n2EDM project at the Paul Scherrer Institute (PSI, Villigen, Switzerland) aims at improving on the sensitivity compared to the experiment with the current best limit on the neutron Electric Dipole Moment (nEDM), $|d_n| < 3 \times 10^{-26}\, e\,\mathrm{cm} \quad (90\,\%\,\mathrm{C.L.})$, published by the RAL-Sussex-ILL collaboration in 2006 [1], by an order of magnitude in a decade. As discussed below, reaching a sensitivity close to $10^{-27}\, e\,\mathrm{cm}$ will either make electroweak baryogenesis highly unlikely in the absence of signal, or lead to the discovery of a non-zero nEDM, *i.e.* to a source of CP violation beyond the Standard Model of particle physics (MS).

The n2EDM project is the follow-up of a running experiment at PSI, based on an upgraded version of the RAL-Sussex-ILL apparatus. The collaboration is composed of 30 physicists and 9 PhD students coming from 12 laboratories (7 countries). Eight of these physicists are from French laboratories: CSNSM Orsay, LPC Caen and LPSC Grenoble. This experiment uses the newly built Ultra Cold Neutron (UCN) source whose commissioning started end of 2010 and which is now operating reliably.The UCN density is however still a factor more than 10 lower than anticipated. It has to be noted that the UCN density has been continously improving since start-up. Another factor of 10 improvement can still be anticipated, however, this improvement will not be the basis of the arguments presented below.

The nEDM@PSI collaboration (see appendix A) has started the design of the n2EDM apparatus in view of its delivery around 2018. The three IN2P3 groups naturally intend to pursue their involvement in this measurement and are intending to contribute both to the design, to the construction and of course to the operation of the n2EDM apparatus.

In this document, we will first discuss the physics motivations in the light of the recent LHC results. In a second part, after giving a status report of the UCN source, we will present the running experiment and the projected nEDM sensitivity after the current data taking period. A third part will be devoted to the n2EDM project with the description of the concept, the expected improvements with respect to the present apparatus and finally the projected sensitivity. We will then recall the international context of the nEDM measurement and finally describe our foreseen contributions.

2 nEDM in the LHC era

The existence of a non-zero electric dipole moment (EDM) for a spin 1/2 particle such as the neutron would imply the violation of the CP symmetry. The Standard Model of particle physics contains a single source of CP violation, namely the δ phase of the Cabibbo-Kobayashi-Maskawa matrix, that accounts for the observed CP violation in K and B mesons. The induced neutron EDM expected from the δ phase is tiny, $d_n \approx 10^{-32}\, e\,\mathrm{cm}$. This value is to be compared to the current best limit obtained at ILL in 2006 [1]: $|d_n| < 3 \times 10^{-26}\, e\,\mathrm{cm} \quad (90\,\%\,\mathrm{C.L.})$

Therefore, improvements of the neutron EDM measurement is motivated by the potential discovery of a new source of CP violation beyond the Standard Model. As for any low energy observable, the new physics at a high energy scale (the TeV scale for instance) manifests itself via virtual effects. Figure 1 shows the loop diagram contributing to a quark EDM via the CP-violating vertices of heavy scalars and fermions with masses M.

Generically the neutron EDM induced by such a loop amounts to [2]

$$d_n \approx \left(\frac{1\,\mathrm{TeV}}{M}\right)^2 \times \sin(\phi) \times 10^{-25}\, e\,\mathrm{cm} \tag{1}$$

where M is the mass of the particles running in the loop. In this case the heavy particles couple strongly with the quark (such as the SUSY coupling between quark, squark and gluinos) with a CP-odd vertex multiplied by $\sin(\phi)$. The CP-odd part usually originates from the imaginary part of some parameter in the Lagrangian and ϕ would then correspond to the CP-violating phase of that specific parameter. Thus, considering natural CP violation ($\sin(\phi) \approx 1$) in the new heavy sector, the nEDM is sensitive to new physics at the multi-TeV scale.

Interplay between nEDM and LHC to probe Supersymmetry

The Minimal Supersymmetric extension of the Standard Model contains potential sources of CP violations that could generate a sizable EDM. Namely, the trilinear coupling A and the μ parameter of the Higgs potential could be complex and thus bear CP-violating phases. A quark EDM is then generated by a squark-gluino loop of the type depicted in Fig. 1.

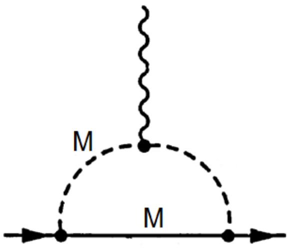


Figure 1: One loop diagram contributing to the quark EDM. The quark EDMs then transfer almost directly to the neutron EDM.

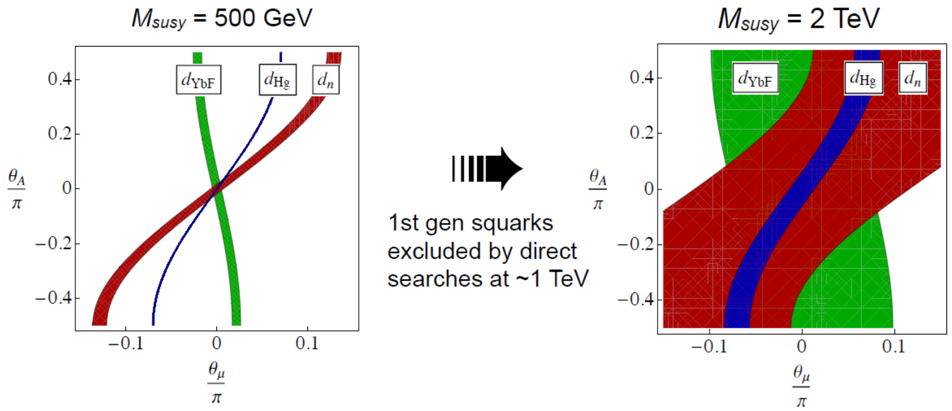


Figure 2: Allowed values of SUSY CP-violating phases from neutron EDM (red), mercury EDM (blue), electron EDM (green). The masses of squarks and gluinos are assumed to be $M = 500$ GeV (left plot, now excluded by the LHC) and $M = 2$ TeV (right plot, still allowed by the LHC). Figure taken from [3].

Before the LHC was started, the benchmark value for M was set to $M = 500$ GeV, in order for SUSY to solve the hierarchy problem. Fig. 2 shows the limits on the phases ϕ_A and ϕ_μ from the non-observation of the neutron, electron, and mercury EDMs. The EDM limits constrain the CP-violating phases to be tiny, of the order of 10^{-2} whereas they are expected to be of the order of unity from naturality considerations.A clear advantage of our collaborative effort is, however, that we have a running and very well performing system at hand. This includes the possibility to continously improve and test future options while implementing tested solutions for n2EDM. This situation was known as the “SUSY CP problem”.

Now, after two years of operation of the LHC, no superpartners have been found in the mass range below the TeV, pushing the SUSY scale at higher energy. It appears that SUSY might not be the solution to the hierarchy problem. Still, SUSY remains an appealing SM extension to provide a candidate for the Dark Matter WIMP and to help the unification of coupling constants at the GUT scale. As an other consequence of the non observation of superpartners, the “SUSY CP problem” has relaxed. The present limits on EDMs are already constraining the superpartners masses at the multi-TeV scale if the CP-violating phases are set to “natural” values. For a recent analysis of the EDM constraints in SUSY scenarios with heavy superpartners - so called split Supersymmetry - see [4].

Extensions of the Standard Model of particle physics such as Supersymmetry are designed to address unsolved issues such as the hierarchy problem, the nature of the Dark Matter and Dark Energy, neutrino masses, quantization of gravity, etc. Inevitably these extensions come with additional free parameters containing generically CP violating phases. Therefore, when confronted to the stringent EDM limits, the proposed SM extensions have to adapt by finding a way to suppress the unwanted CP-violation. CP violation is often considered as a non desirable feature by model builders, because most of the problems the extensions are supposed to solve have nothing to do with CP violation in the first place. There is however one single, albeit essential, unsolved problem which demands new CP violation sources: the matter-antimatter asymmetry of the Universe.

Probing the baryogenesis with nEDM

The Universe is not matter-antimatter symmetric. Practically all the baryonic and leptonic antimatter present in the primordial plasma has annihilated with matter. The slight excess of matter is quantified by the ratio of baryon to photon density $\eta = n_b/n_\gamma \approx 6 \times 10^{-10}$, extracted both from the Cosmic Microwave Background observations and from the analysis of primordial nucleosynthesis. In 1967 Sakharov proposed a set of three necessary conditions in order to generate the baryon asymmetry of the universe (BAU) out of an initially symmetric state: (i) the existence of baryon number B violation processes (ii) C and CP-violating interactions (iii) interactions out of thermal equilibrium. From the third condition we suspect that the asymmetry has been generated during a phase transition in the early universe.

The generation of the BAU during the electroweak phase transition is an appealling possibility that leads to testable consequences, this scenario is referred to as *electroweak baryogenesis* (see [5] and references therein). Wheras the first Sakharov condition is fullfilled in the Standard Model by the sphaleron B-violating process, conditions (ii) and (iii) require physics beyond the SM. To fulfill condtion (iii), the electroweak phase transtion must be strongly first order. This would have been the case in the SM if the Higgs boson were lighter than 42 GeV. From the recent LHC data we know that the Higgs mass is about 126 GeV and the electroweak phase transition is a smooth second order transition if no new physics is present in the scalar sector. The situation is quite similar regarding condition (ii): the SM does not provide enough CP-violation to create the entire baryon asymmetry.

The failure of the SM to allow for the electroweak baryogenesis could be a hint toward the presence of new physics that may be probed both by collider experiments and EDM searches. The most studied example is the minimal SUSY extension of the SM that has enough flexibility to compensate for the two deficiencies of the SM: the presence of an extended scalar sector could lead to a strongly first order phase transition and the extra CP-odd phases could provide the missing CP-violation (see [6] for a recent analysis on the topic). This scenario is on the verge of being excluded - or discovered - by both EDMs and LHC.

Another interesting example of SM extension consists in the addition of dimension-six operators in the Higgs sector [7]. In this scenario, so called *minimal electroweak baryogenesis*, the particle content of the SM is left unchanged. The strengthening of the first-order phase transition is provided by a modification of the mexican-hat Higgs potential by a dimension-six operator of the type $-\frac{1}{\Lambda^2}(H^\dagger H)^3$. In order to satisfy the third Sakharov condition the threshold scale must be set to $500\,\mathrm{GeV} < \Lambda < 700\,\mathrm{GeV}$. The extra CP-violation required to satisfy the second Sakharov condition is provided by another set of CP-odd dimension six operators that couple the Higgs field to quarks and leptons, with a threshold scale Λ_{CP}. One has to set $\lambda_{\mathrm{CP}} \approx 700$ GeV to account for the en-

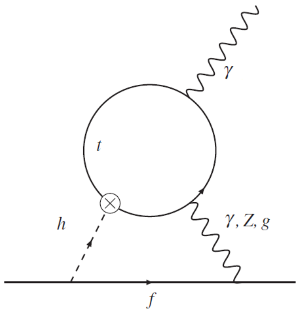


Figure 3: Loop diagram contributing to the nEDM in the presence of a CP-odd Higgs coupling of the type discussed in [7].

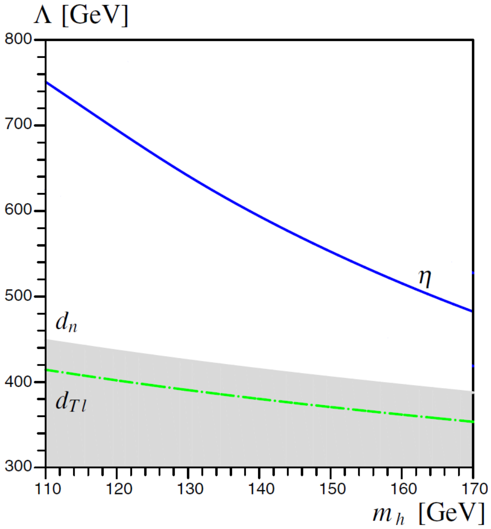


Figure 4: The plot is taken from [7] discussing the minimal electroweak baryogenesis. The shaded region is excluded by the nEDM limit, the green line correponds to the electron EDM. The blue line corresponds to the scale Λ_{CP} needed to account for the observed baryon asymmetry.

tire baryon assymetry. The CP-odd Higgs couplings also generate an EDM for fermions through the loop diagram shown in fig. 3. Figure 4 shows the nEDM limits in the parameter space $\Lambda_{\rm CP} - m_h$ where m_h is the Higgs mass (now we know $m_h = 126$ GeV). It is apparent that an improvement of the nEDM limit by a factor of 3 could exclude the minimal electroweak baryogenesis (the nEDM scales as $1/\Lambda_{CP}^2$).

3 Status of the PSI UCN spallation source

In June 2011 the Swiss Federal authorities granted operation approval and since then the PSI UCN source has delivered UCN, with its beam time sharing between the nEDM experiment and tests to improve the understanding of the source performance and increase its UCN output. The UCN source is operated at up to 1 % duty cycle using the full available proton beam (590 MeV) of up to 2.4 mA on target and with beam kicks of a maximum length of 8 s.

Fig. 5 displays the improvement in UCN output by a factor of ~100. since the first beam on target in Dec.2010. 2013 saw already a 40 % increase with respect to the best before. The increase in 2013 *e.g.* can be attributed to an increase in deuterium moderator mass and to less proton beam loss after improved beam tuning.

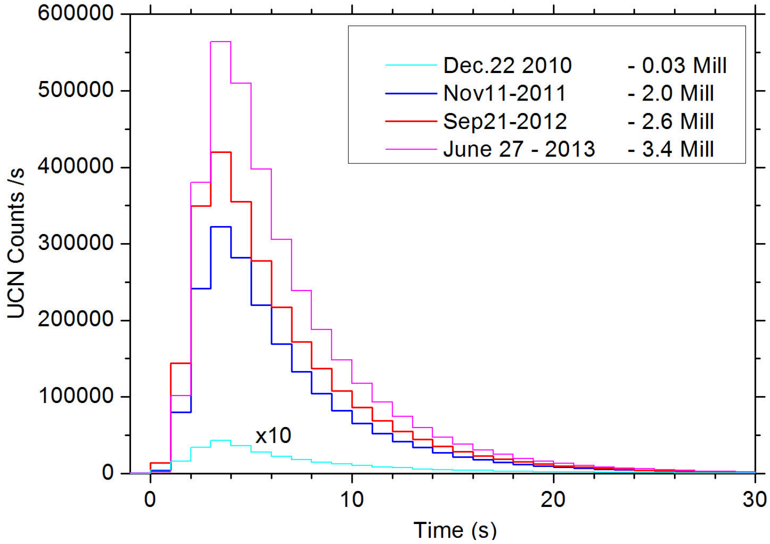
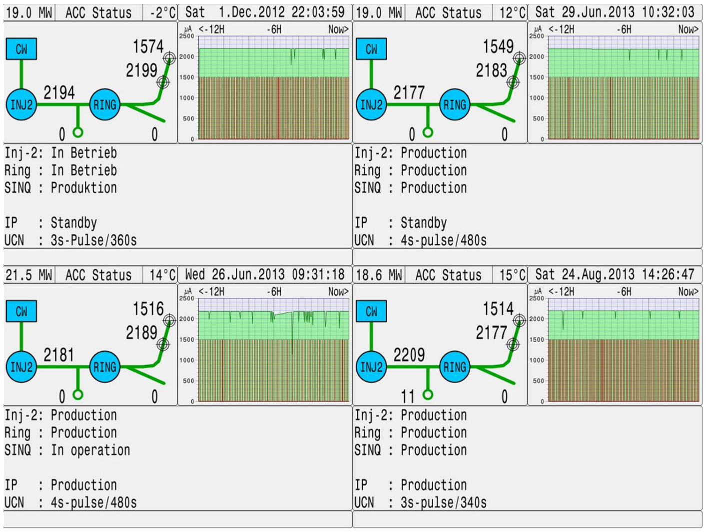


Figure 5: In order to unambiguously compare the UCN output over years and with different conditions of solid D_2 we have defined a standard beam operation: 2s long proton beam kicks with full beam current without any mechanical shutter operation. The latter means, that all UCN are quickly lost out of the storage vessel. The UCN count rate in such a benchmark kick is then observed with a CASCADE counter at beam port West-1.

In order to compare the relevant UCN output which is available to experiments one can compare two different important numbers.

1. total number of UCN per beam kick: for a typical beam kick of 4s length and 2.2 mA proton current 23×10^6 UCN are measured at beam port West-1 and can be delivered to an experiment every 6 minutes.
2. density of UCN: a NiMo coated UCN storage vessel of 25 ℓ volume was operated at the beam port. In a storage experiment we measured after 3 s of storage a UCN density of above 30 UCN/cm^3, taking into account the known transmission factor 0.7 of the detector window, however without any other correction for efficiencies or extrapolations.



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19.0 MW  ACC Status  -2°C  Sat  1.Dec.2012 22:03:59
Inj-2: In Betrieb
Ring : In Betrieb
SINQ : Produktion

IP   : Standby
UCN  : 3s-Pulse/360s
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19.0 MW  ACC Status  12°C  Sat 29.Jun.2013 10:32:03
Inj-2: Production
Ring : Production
SINQ : Production

IP   : Standby
UCN  : 4s-pulse/480s
```

```
21.5 MW  ACC Status  14°C  Wed 26.Jun.2013 09:31:18
Inj-2: Production
Ring : Production
SINQ : In operation

IP   : Production
UCN  : 4s-pulse/480s
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18.6 MW  ACC Status  15°C  Sat 24.Aug.2013 14:26:47
Inj-2: Production
Ring : Production
SINQ : Production

IP   : Production
UCN  : 3s-pulse/340s
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Figure 6: Accelerator status display for typical days of nEDM data taking showing the UCN kicks - arbitrary height 1.5 mA - and the very constant proton beam current, for days in 2012 and 2013.

Fig. 6 shows 4 typical days of UCN beam serving the nEDM experiment with a very stable proton beam current. Given the typical nEDM measurement time of about 250 s, pulse sequences of 3 s every 330 s or 4 s every 480 s are optimal operation modes from a statistics point of view.

The availability of UCN for experiments has increased largely in the first 3 years of operation. Full UCN operation days, where the UCN source was cold, increased from 23 days in 2010, to 224 in 2011 up to 275 in 2012. The integrated proton beam current on the UCN spallation target increased from 0.02 mAh (20 pulses in 2010), to 8.2 mAh (~2000 pulses in 2011) and to 28.87 mAh (~13600 pulses in 2012). Costly upgrades of the groundwater cooling system and the cooling circuits of the helium cryo plant were done and are being planned for the next shutdown, in order to provide an even larger availability of UCN.

Spallation target performance

The neutron production at the UCN spallation target was tested via comparison of a full "as built" MCNP-X simulation of the target, the subsequent moderation in the thermal heavy water moderator and its environment with gold foil activation measurements. An aluminum tube was installed along the outside of the UCN vacuum tank. Several gold foils mounted on a rope were inserted in this tube, from 1 m below the target up to 4 m above the target. Gammas from the activation during one beam kick were subsequently measured. Fig. 7 shows the comparison of the measured activation height profile with the simulation. From that we conclude that the thermal neutron flux is well understood. The resulting neutron flux in the deuterium vessel is about a factor of 2 low when comparing the first design estimate with the built system.

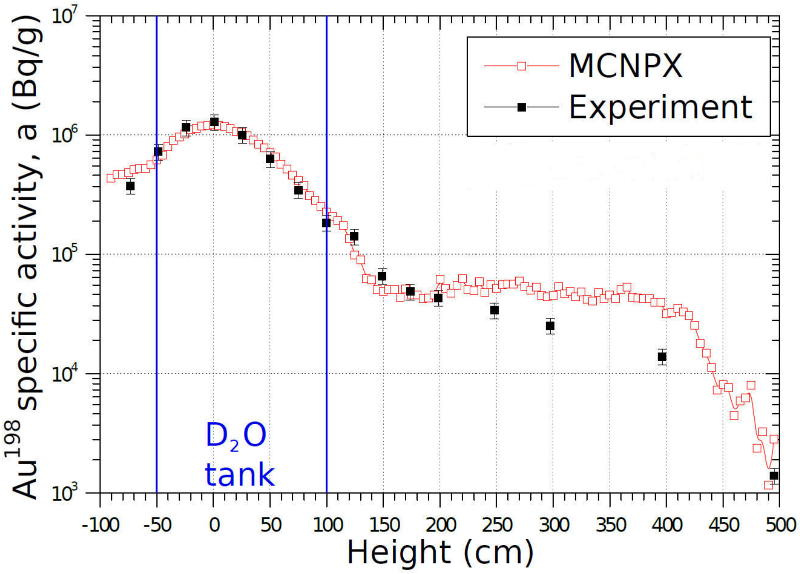

Figure 7: Specific activity measured in gold foils irradiated along the UCN vacuum tank. Measurements are compared with a full MCNP-X simulation. Height 0 defines the center of the lead spallation target. The D_2O tank is indicated.

UCN measurements to better understand the source performance are being continued in 2013, including measurements of gaseous D_2 moderators at various pressure and temperatures, solid deuterium with different D_2 masses and different freezing conditions etc.

We believe that there is still a factor of more than 10 further improvement in UCN yield possible. The current program vigorously aims at determining or excluding reasons for neutron losses and realizing the possible improvements.

4 The nEDM experiment at PSI

4.1 Principle of the measurement

The neutron EDM measurement is based on the analysis of the Larmor precession frequency of neutrons, stored in a volume permeated with electric and magnetic static fields either parallel or antiparallel. For such configurations, the precession frequency ν_L reads

$$h\nu_L = \mu_n B \pm d_n E$$

where μ_n and d_n are the magnetic and electric dipole moments of the neutron. The frequency difference of these two configurations gives directly access to the neutron EDM:

$$d_n = h\Delta\nu_L/4E.$$

To measure the precession frequency, we use the Ramsey's method of separated oscillatory fields which provides a precision of the order of 10^{-6}. The main experimental challenge consists in achieving a magnetic field homogeneity at the level of 10^{-5} over a volume of typically 20 ℓ, while maintaining a temporal stability of about 10^{-7} over 100 s. Atomic magnetometry and magnetic shielding techniques are therefore at the core of such a measurement. All experiments use Ultra Cold Neutrons (UCN) whose long storage times allow for an optimal sensitivity. The corresponding statistical precision on the neutron EDM is given by

$$\sigma(d_n) = \frac{\hbar}{2\alpha E T\sqrt{N}} \tag{2}$$

where E is the electric field intensity, T the precession time, α the visibility (related to the polarization of the UCNs) and N the total number of detected UCN. Both α and N decrease exponentially with the storage time, giving an optimal storage time in the range 180-200 s. The visibility α also depends on the initial neutron polarisation, the magnetic field homogeneity and the efficiency of the neutron spin analysis.

4.2 The upgraded RAL-Sussex apparatus

For the current data taking, we are using an upgraded version of the RAL-Sussex spectrometer which holds the best nEDM limit [1] and that we moved from the ILL to the PSI in 2009. This spectrometer operates at room temperature and is connected to the new PSI UCN source. One distinct feature of this apparatus is the availability of a Hg co-magnetometer: a vapor of polarized ^{199}Hg atoms fills the same volume as the UCNs and provides the same space-time average of the magnetic field as seen by the neutrons. Fig. 8 shows the precession chamber, composed of a polystyrene (PS) insulator and 2 disk-shaped electrodes, inside the vacuum tank. The top electrode is connected to the HV power supply.

Since we took over the operation of this apparatus in 2005, we have conducted a comprehensive program of rejuvenation of the various components of the setup, from the data acquisition system and the electronic modules to the HV power supply, in order to improve the reliability of the system. We also systematically attempted to improve its performances with a twofold objective: increase the statistical sensitivity and, at the same time, gain a better control on systematics. The most significant improvements are dicussed below.

Insulator ring The insulator ring was initially made out of quartz which combines a high resistivity to a moderate Fermi potential (90 neV). The PSI group extensively looked for a new material with a higher Fermi potential (thus

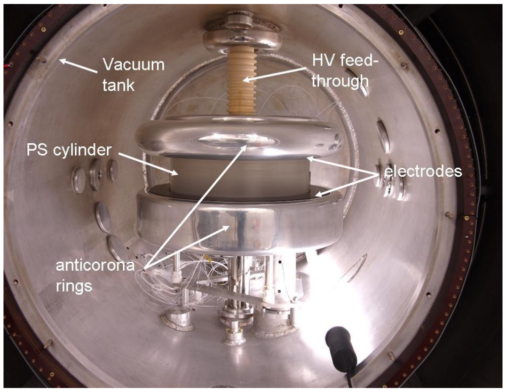

Figure 8: View of the UCN precession chamber.

allowing for the storage of higher energy neutrons), while preserving all the other nice features of the quartz: a high resistivity and good properties for the storage of polarized UCNs and Hg atoms. After several trials, a successfull candidate was identified: the polystyrene coated with deuterated polystryrene. Test measurements at the ILL have shown an 80 % increase in the number of stored UCNs [8].

Magnetic field homogeneity The magnetic field homogeneity influences directly the transverse relaxation time of the neutrons polarization T_2 and consequently the value of the visibility α. When we started working on the apparatus in 2004, the performances were severely degraded after a vacuum accident in 2003 which caused a magnetic anomaly. T_2 values could not exceed 150 s whereas they used to be larger than 500 s. In 2008, with 3D magnetic field mapping, we succeded to identify and cure the source of the problem. Thanks to the presence of the PTB Berlin group in our collaboration, we have also developed a much improved (in terms of reproducibility and remanent field) degaussing procedure of the magnetic shield. Moreover, their participation ensures the access to the best shielded room worldwide BMSR-2. We use this facility to regularly control the magnetic properties of all bulky equipments (like electrodes) entering into the vacuum tank. We have in addition developed a sensitive gradiometer at PSI which allows a control of small objects. As a result, we have now the best T_2, reaching values as high as 1000 s.

Electric field intensity All HV related equipments (HV power supply, cable, vacuum feedthrough) have been renewed. Despite the presence of numerous optical fibers needed to operate the Cs magnetometers, we have demonstrated that we can reach appreciably higher HV values (120 kV as compared to 100 kV).

Improvements discussed so far help to improve the statistical sensitivity. As for the next item, it deals with the control of systematics.

Vertical gradient control To measure the magnetic field in the precession chamber during nEDM data taking, we have complemented the Hg comagnetometer by an array of external Cs magnetometers, developed within our collaboration by the group of Fribourg (Swiss). These highly sensitive magnetometers are placed below and above the precession chamber, thus giving a direct measurement of the field modulus vertical gradient. This key feature provides a much better control of magnetic field related systematic errors and has already been used to obtain the first competitive measurement of the magnetic moment of the neutron with UCNs, at a level comparable to the best measurement (a corresponding paper is in preparation).

4.3 Data taking in 2012-2013

In 2012, we got nearly four months of UCN beam, starting in September. Most part of the beam time was used to tune the spectrometer towards its best performances and also to test the UCN source. Only the last six weeks were devoted to nEDM data taking, with 1608 cycles recorded. In 2013, the UCN source started late June and has already delivered 3400 cycles for the nEDM data taking.

Statistical sensitivity

Using expression 2, the achieved sensitivity in 2012 and 2013 is summarized in Table 1.

	RAL-Sussex-ILL		PSI 2012		PSI 2013	
	Best	Mean	Best	Mean	Best	Mean
E (KV/cm)	8.8	8.3	8.3	7.9	12	10.3
Nb UCN	14 000	14 000	9 000	5 400	8 400	6 300
T precession (s)	130	130	200	200	180	180
α	0.6	0.45	0.65	0.57	0.62	0.56
Sensitivity per cycle ($\times 10^{-25}$ e.cm)	43	57	32	50	27	39
Nb cycle per day	360	360	150	150	200	200
Sensitivity per day ($\times 10^{-25}$ e.cm)	**2.3**	**3.0**	**2.6**	**4.0**	**1.9**	**2.8**

Table 1: Status of statistical sensitivity of the RAL-Sussex spectrometer at PSI.

In 2013, we succeded to improve our instantaneous sensitivity from 4×10^{-25} $e\,$cm per day to 2.8×10^{-25} $e\,$cm, the best value for this apparatus so far. This is due to an increased HV value and a better visibility. As compared to the RAL-Sussex-ILL setup, increasing the HV was challenging because of the addition of the Cs magnetometers. Concerning the visibility, we benefited from an improved T_2 as discussed above. We could also slightly increase the number of cycles per day by using a 3 s proton pulse duration on the spallation target (4 s in 2012).

Figure 9 shows the integrated sensitivity of the ongoing data taking : it went from 1.2×10^{-25} $e$cm to 6.7×10^{-26} $e$cm in 2013 (up to September). The combined sensitivity is now 5.9×10^{-26} $e\,$cm.

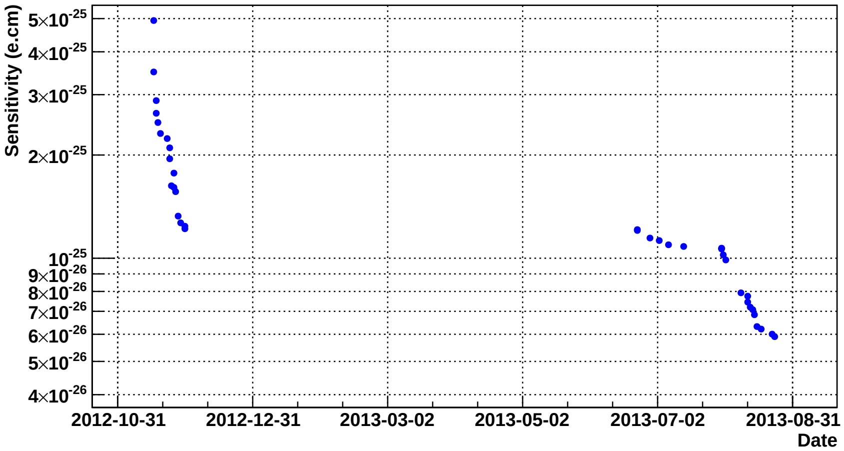

Figure 9: Integrated statistical sensitivity in 2012-2013.

To conclude, we are now running with an instantaneous sensitivity slightly better than the RAL-Sussex-ILL experiment. Since the previous nEDM limit was based on more than 4 years of regular data taking, we cannot hope improving it significantly in a reasonable time without better performances of the UCN source. This could be achieved by improving the UCN transport into the experiment and by approaching the nominal performances of the source, a goal which is actively pursued by PSI. In addition, we can expect getting an even better intrinsic sensitivity of the apparatus by the implementation of the new UCN detection system developed by the LPC Caen. It will allow to simultaneously analyze the 2 UCN spin components and could result both in a better visibility and an increased number of detected UCNs.

Systematics

The current status of the error budget is presented in Table 2 and compared to the previous RAL-Sussex experiment [1] published in 2006. Already our control over systematics is improved, thanks to (i) the use of Cesium scalar magnetometers and (ii) intensive magnetic field mappings and careful control of dipole contaminations on the inner components. The systematic effects are divided in two main categories: (i) direct effects correspond to frequency shifts of UCNs and mercury, linear in the electric field, these effects are independent of the magnetic field homogeneity ; (ii) indirect effects are related to the so-called geometric phase of mercury, resulting from the combined effect of the relativistic $\mathbf{v} \times \mathbf{E}$ motional field and the magnetic field gradient.

The main direct systematic effect, namely the uncompensated B-Drifts, arises from a possible magnetic field change induced by the electric field reversal. Using the Cesium magnetometers array, arranged around the precession chamber, we are able to exclude such a direct correlation. We have gained a factor of 2 in the control over this effect as compared to the previous experiment and further improvements are forseen with the continuation of the data taking.

We have also achieved significant progress concerning the indirect effects. First, a new theoretical description of the geometric phase shift [9] has been developped, valid for arbitrary magnetic field shapes. The existing theory was only valid for a uniform gradient and the systematic effect due to localized dipoles was poorly accounted for. Second, we improved the quality and the control of the magnetic field homogeneity in the precession chamber. Dedicated field mapper robots have been used for several intensive 3D field mapping campains to measure the transverse field components. The analysis of the latest campain is still ongoing and the error quoted as "Quadrupole Difference" is expected to improve.

Overall, we would quote for the current dataset a systematic error of $4 \times 10^{-27}\, e\,\mathrm{cm}$, well below the statistical sensitivity.

Effects	Status	RAL/Sussex/ILL (2006)
Direct Effects		
Uncompensated B-Drifts	0.5 ± 1.2	0 ± 2.4
Leakage Current	0.00 ± 0.05	0 ± 0.1
$V \times E$ UCN	0 ± 0.1	0 ± 1
Electric Forces	0 ± 0.4	0 ± 0.4
Hg EDM	0.02 ± 0.06	-0.4 ± 0.3
Hg Direct Light Shift	0 ± 0.008	0 ± 0.2
Indirect Effects		
Hg Light Shift	0 ± 0.05	3.5 ± 0.8
Quadrupole Difference	1.3 ± 2.4	-1.3 ± 2
Dipoles		-5.6 ± 6.3
At the surface	0 ± 0.4	
Other Dipoles	0 ± 3	
Total	1.8 ± 4.1	-3.8 ± 7.2

Table 2: Status of the constrain on systematic effects in units of $10^{-27} e \cdot \mathrm{cm}$.

5 The n2EDM project

5.1 The general concept

The general concept of the new spectrometer is defined but most of the details are not settled yet. The main idea is to simultaneously measure the two field configurations (parallel and anti-parallel electric and magnetic fields). The measurement is performed in two different precession chambers vertically arranged one on top of each other (Fig. 10). The separating piece is the HV electrode, the top and the bottom walls constitute the ground electrodes. The electric field direction is opposite in the two chambers. A dedicated coil surrounding the central vessel provides the main B_0 field. Magnetic field monitoring will

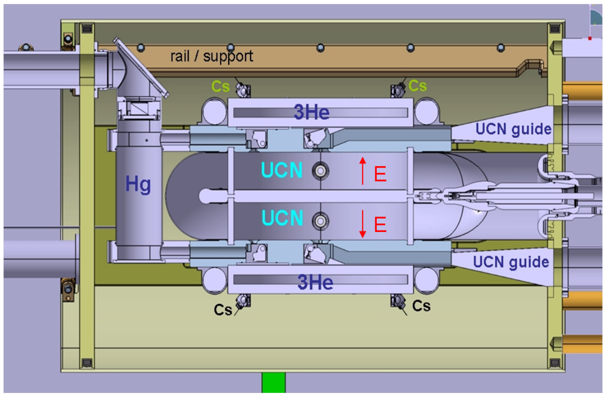

Figure 10: Scheme of the double precession chamber foreseen for the n2EDM spectrometer.

be performed with a co-magnetometer as well as with external vector magnetometers closely installed around the central vessel. The B_0, RF, gradient and correcting magnetic fields, will be provided by a movable system of coils surrounding the inner part of the apparatus. The ensemble is mounted inside a multilayer passive magnetic shield (Fig. 11).

This magnetic shield, which is about to be ordered, will have a shielding factor above 10^5, larger than the RAL-Sussex one (around $10^3 - 10^4$). The field gradient in the innermost part of the shield has been requested to be lower than 1 pT/cm (the minimal gradient is about 10 pT/cm within RAL-Sussex). Additionally, a specific set of coils is planned for the shield demagnetization: the residual field after degaussing will be below 100 pT (below 2 nT with the current system).

Concerning the B_0 field generation, a set of coils is currently being designed, using a novel promising technique [12] to reach the best uniformity. In addition, studies performed at LPSC on stabilized current sources for the B0 coil will be pursued to reach a stability of the order of 10^{-7} over 100 s (100 fT/1 μT).

Based on our previous experience, we will continue using a combination of a Hg comagnetometer and external atomic magnetometers to perform the online monitoring of the magnetic field. In addition to the Cs magnetometers, a ^{3}He based gradiometer will be installed around the UCN volume. A possible arrangement of the magnetometer system is shown in Fig. 10.

5.2 Expected statistical sensitivity

To significantly improve the intrinsic sensitivity of the n2EDM apparatus as compared to the RAL-Sussex spectrometer, we will play on the 4 parameters entering in expression (2). The expected improvement on these parameters is discussed below.

Number of UCN In order to optimally use the PSI UCN source, the simulations have shown that the apparatus should be at the same level as the UCN guide. This configuration was impossible with the RAL-Sussex spectrometer

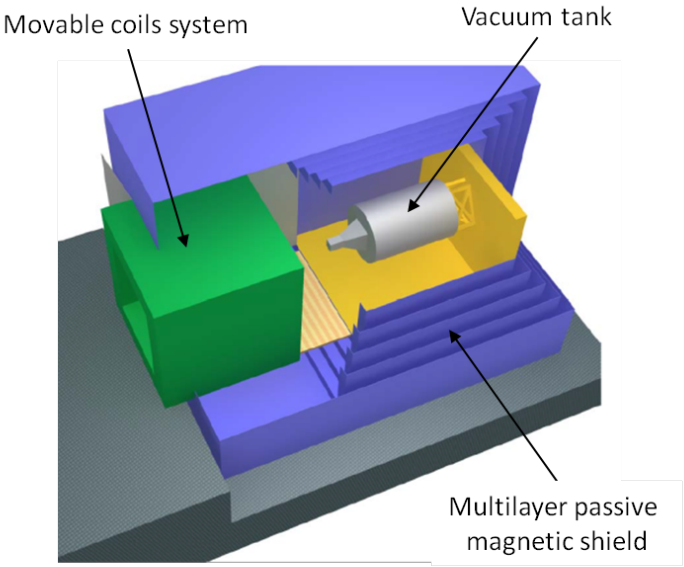

Figure 11: General lay-out of the n2EDM apparatus.

for which the storage chamber is about 1.2 m above the horizontal beam line. Measurements at the WEST-1 beam line, have confirmed that the UCN density is indeed about 30 times higher in the former geometry [10]. The new spectrometer will be therefore filled from the side. Adapting the results obtained on WEST1 to the n2EDM apparatus, one may expect a UCN density ranging between 4 and 10 UCN/cm^3 *i.e.* a factor of improvement of 2-3 in sensitivity.

Obviously, we will also benefit from an increased volume due to the double chamber setup for which a total volume of 50 ℓ is foreseen. Knowing that the volume of the current storage cell is 21 ℓ, an additional gain of 1.5 in the statistical sensitivity will be obtained.

Electric field intensity E With the n2EDM set-up, the equipment surrounding the storage chamber (especially the Cs magnetometer) will be at ground. As a result, the risk of breakdown, which is the current limiting factor, will be reduced and an increase of the electric field intensity by about 30 % is envisaged (the current value is about 10 kV/cm). The ultimate limitation will probably be due to the dependence of the Hg magnetometer performance and on the electric field strength.

Storage time T and visibility There is no clear evidence that these two parameters could be appreciably improved. The storage time T may be increased if a better coating for the storage chamber is used. We will therefore continue our R&D program on coatings and materials for optimal UCN storage. For instance, investigations on the use of diamond as a new coating material have started.

The visibility, *i.e.* the apparatus capability to polarize, hold, transport and analyze the UCN polarization, may be slightly improved along with the transverse relaxation time T_2. Assuming a fully polarized UCN beam and no depolarization between the polarizer and the analyzing stage, the maximum reachable visibility is limited by the foil analyzing power for which a value as high as 0.95 has been measured. A mean visibility of $\approx$0.8 should be achievable (current value is $\approx$0.6).

In summary, including all factors discussed above, the foreseen statistical sensitivity is $5 \times 10^{-25}\, e\,\mathrm{cm}$ per cycle, equivalent to $4 \times 10^{-26}\, e\,\mathrm{cm}$ per day with 150 cycles per day. Assuming the performances of the UCN source will remain at today's level, a sensitivity of $2 \times 10^{-27}\, e\,\mathrm{cm}$ could be achieved after 4 years with 100 full days of operation.

5.3 Systematics with n2EDM

As already mentioned, for the contol of systematics of the n2EDM apparatus, we will follow the same successfull strategy used for the current experiment. It relies essentially on a combination of a Hg comagnetometer for the online measurement of the magnetic field with external magnetometers (Cs and He) to control gradients. Due to the much better quality of the new magnetic shield and coils, the magnetic field inhomogeneities will be noticeably reduced. Consequently, the most problematic systematic errors resulting from the geometric phase will be automatically reduced, we believe down to the $10^{-28}\, e\,\mathrm{cm}$ region.

Moreover, we will benefit from a new type of Cs magnetomers, the so-called vector magnetometers which will provide a measurement of the longitudinal and *transverse* components of the magnetic field. These magnetometers will be used for the online control but also to perform offline field maps with a much better precision than the standard fluxgate sensors. From these new tools, we expect a qualitative jump in our control of the 3D features of the magnetic field. Tests of fhe first prototype are ongoing.

In the hypothesis the UCN source performances will remain at the present level, our current control over systematics is practically sufficient for the planned statistical sensitivity. In case the source will reach its nominal density, we are confident that a global systematic error of $5 \times 10^{-28}\, e\,\mathrm{cm}$ could be achieved.

5.4 Current status

The first steps towards the construction of the n2EDM apparatus have started. The new thermohouse that will host the future spectrometer has already been built. It is currently installed in a building near the experimental area. Once the ongoing data taking will be over, the thermohouse will be moved in the south area of the UCN source buiding at the place of the existing experiment.

Most importantly, after a long phase of design and extensive discussions within the collaboration, the specifications of the passive magnetic shield have been fixed. A WTO call is now opened since September 2013. If everything runs smoothly, we hope to get the shield delivered at PSI end of 2015.

In parallel, investigations about the n2EDM coils system have started. We are going to use a new promising technique developed at the University of Kentucky [12]. This technique allows to design coils producing an inner field uniformity better than 10^{-5} and essentially no magnetic field outside thanks to double layer coils. This latter feature will prevent the magnetization of the shield and decouple the B_0 field from the shield properties. In collaboration between the LPC Caen and the University of Kentucky, the project DISCO (Double Iso-Scalar potential COil) has been launched. It consists in designing of a small quarter-scale single-coil prototype (currently under study). The construction will happen in the first semester of 2014. Measurements will determine the ultimate uniformity achievable with this type of coils.

6 The international context

There are currently five other nEDM projects worldwide, all at very different stages. Apart from our experiment, there are only two spectrometers in operation. The old PNPI spectrometer has been installed at the PF2 UCN source at the ILL and has started taking data in 2013. The next step is to move during the long ILL shut-down the apparatus to a different position of the PF2 UCN source to get more neutrons. After 2 years of measurement, they claim a limit close to $10^{-26}\,e\,\mathrm{cm}$ could be approached. Later, the apparatus will be moved back to PNPI where a new UCN source will be built. The British project CRYOEDM, also at the ILL, is still in the commissioning phase. It uses the technique of downscatteting of cold neutrons in superfluid helium to produce UCNs. The progress has been considerably slowed down due to cryogenic issues. They plan to take their first nEDM data in 2 to 3 years. A German project at Munich plans to use the new UCN source under construction at the reactor FRM-2. The progress with respect to the detector is going on rapidly (the magnetic shield is already installed *in situ*), however the UCN source has not started yet and its performances are unknown. The two other projects (RCNP-TRIUMF and SNS-Oak Ridge) are in the R&D phase and will start real data taking around 2020 at best. For more information about all EDM projects, see the EDMs worldwide page [14].

All collaborations claim to reach a sensitivity level around or below $10^{-27}\,e\,\mathrm{cm}$ by 2020. However, all experiments are facing great difficulties with the new UCN sources, based either on solid deuterium or superfluid helium, and are far from the anticipated densities of a few 100's of UCN/cm^3.

7 Foreseen French contributions

7.1 Tasks

Since 2006, both LPCC and LPSC have significantly contributed to the upgrade of the RAL-Sussex apparatus with the support of the technical groups of both laboratories. Two fast detectors (NANOSC), based on ^{6}Li doped glass scintillators, with their readout electronics (FASTER) were developed at LPCC. Both systems are currently running beneath the spectrometer. Caen also furnished recently a simultaneous spin analyser. It will be tested during this autumn. Major contributions about the magnetic field within the storage chamber (3D field mapping campaigns since 2006 and 3D field parameterization) have been performed. Specific mechanical studies have also been carried out (for instance, the RAL-Sussex spectrometer support). The new central electronic module for the control of the data acquisition system has been developed at LPSC together with the stable B_0 current source.

For n2EDM, we wish mainly to carry on contributing to the same tasks :

1. Detailed design of the spectrometer

   The mechanical design and the conception of several parts of the new spectrometer are foreseen (vacuum tank, electrodes, mechanical support...‘). A first list of items will be defined this autumn. This contribution is valuable for the project because the PSI mechanical staff is fully involved in the onsite development of the new X-Ray Free- Electron Laser (SwissFEL).

2. UCN detection and front-end electronics

   Investigations have already started about a second generation detector. It is a fast ^{3}He gas detector either based on the GEM technology or on the scintillation process in the gas. Further tests are needed to select the best solution. The goal is to further decrease the gamma-ray sensitivity and to increase the detection efficiency, keeping the same ability to handle large counting rates. The FASTER acquisition system will perform the readout of the detector.

3. Spin analysis and guiding

   The development of simultaneous spin analyzing systems will be pursued. The spin analysis technique is basically under control but large improvements of the transmission could be achieved using new coatings for the inner walls of the system. Encouraging results have been obtained with diamond coating (20 % larger Fermi potential than the usual NiMo coating). For n2EDM, two simultaneous spin analyzers and four detectors are required.

4. B-field maps reconstruction

   A magnetic field mapper able to scan the whole space and without metallic parts was designed and built. The data analysis is ongoing and 3D field maps will soon be available, with a precision of a few 100 pT. This know-how in the B field measurement and reconstruction is one of our assets and will be applied to n2EDM

5. Coil design

   In order to remove the coils (B_0, gradients, RF) influence on the permalloy shield, a self-compensated coil, which provides a uniform field in the UCN precession chamber and a null external field is being simulated and will be prototyped in 2013 (see section 5.3).

6. Mercury comagnetometer

   Following our long-standing involvement in the Hg magnetometry, we wish to contribute to the design and construction of the future Hg comagnetometer. To this aim, we need to develop a test bench at LPSC to investigate the known issues (for instance the sensitivity to E-field reversal) and explore new ideas.

7. Mercury Data analysis

   The precision of the mercury comagnetometer is a key element for compensating the magnetic field drifts at the desirable level for n2EDM. An optimal use of the mercury precession signal demands dedicated studies in terms of data processing. Recently we attacked this problem at a deeper level based on MonteCarlo simulations. We intend to pursue these studies to find better algorithms for frequency extraction.

8. Stable current source

   B-field time stability is equally important as the volume homogeneity. For this, ultra stable current sources are needed. Based on our experience with the source currently in use, we will continue an R&D program to produce the sources with the requested stability.

9. Data analysis

   Within the present collaboration there are two separate analysis groups, one centered around the French labs and the other around PSI. The two groups work independently and discuss their results during collaboration meetings. The data analysis is supported by UCN simulations. This working scheme will be transposed to n2EDM.

10. Data taking

    All members of the collaboration have to fulfill an equal share of shifts at the PSI.

7.2 Budget

Since 2006, the overall budget allocated by IN2P3 is around 250 k€ in total. We also received a grant from ANR (2009-2012) of 280 k€.

1. Shifts at PSI

   Overall, there are currently 8 permament staff members and 2 graduate students involved. The annual needs are 45 k€/year. These needs are valid for nEDM and eventually for n2EDM.

2. Equipement

   According to the task section, the requested equipments are listed in the following table 3.

   The participation to the PSI experiment running costs is 15 k€/year.

3. PhD students

   Already 3 PhD students have been achieved and 2 are ongoing. The aim is to continue to have two PhD students between Caen and Grenoble, with extended stay at PSI. The PhD students funding and supervision sharing between us and PSI have been very successful. For the coming years post-docs grants (24 months) will be also asked.

Most of the budget request will be part of a 2014 ANR application. However, we stress that the IN2P3 support for travel expenses and minimal technical developments will be in any case needed.

Task	Item	Cost (k€)
Detection	Scintillating ^{3}He detectors	55
	GEM ^{3}He detectors	125
Spin analysis and guiding coils	Diamond coating	40
	Simultaneous spin system	40
Hg magnetometer	Test bench	70
	n2EDM Hg co-magnetometer design and construction	50
Current source	Design and construction	30
B field mapping and reconstruction	Computer and software	15
Coil design and construction	Self compensated coil	100
General design	Vacuum tank (if granted to the French groups by the collaboration)	100
Total		**625**

Table 3: Costs estimate.

7.3 Manpower

Here is the list of all people from the technical groups who have contributed so far: B. Bougard, D. Goupillère, P. Desrues, D. Grondin, Y. Merrer, E. Perbet for the mechanical design and manufacturing.
O. Bourrion, B. Carniol, G. Dargaud, D. Etasse, C. Fontbonne, J. Homet, E. Lagorio, J. Poincheval, C. Vescovi, for front end electronics and data acqusition.
JF. Cam, M. Marton, J.-F. Muraz, J. Peronnel, M. Tur, C. Vandame, O. Zimmermann for instrumentation and detector.

On table 4 we show the technical department involvement since 2006.

Department	Man year
Mechanical design and manufacturing	8
Front end electronics and data acquisition	6
Instrumentation and detectors	8

Table 4: Engineering and technical staff over the 2006-2013 period.

Related to the task list section 7.1, are presented the foreseen needs for the n2EDM development on table 5.

For the physicists after being a limited number of people we have progressively increased the number of permanent staffs (see Table 6). A new physicist has recently joined us and we will continue our effort to attract more people. Any new CNRS position would be of course very welcome.

Department	Man year
Mechanical design and manufacturing	6
Front end electronics and data acquisition	2.5
Instrumentation and detectors	4

Table 5: Engineering and technical staff estimated over the 2014-2018 period.

S. Roccia	MdC	CSNSM
G. Ban	Professor	LPCC
V. Hélaine	PhD student	LPCC / PSI
T. Lefort	MdC	LPCC
Y. Lemière	MdC	LPCC
G. Quémńer	CR	LPCC
B. Clément	MdC	LPSC
G. Pignol	MdC	LPSC
Y. Kermaïdic	PhD student	LPSC
D. Rebreyend	DR	LPSC

Table 6: Physicists involved in the nEDM and n2EDM.

8 Conclusions

We have shown in this document that we have upgraded the performances of the RAL-Sussex apparatus, installed at PSI since 2009, both in terms of systematics control and intrinsic statistical sensitivity. While UCN source improvements are being realized (a factor of 10 may still be anticipated but progress is slow and difficult to plan) we have already obtained in 2013 the best nEDM statistical sensitivity per day.

In these conditions, continuing the data taking for 3 more years will result in a new nEDM measurement at a level comparable to the present limit but with a better control of systematic effects. If the full factor 10 in the UCN source intensity is recovered, we expect to improve the limit by a factor 3.

In order to reach a significant improvement – allowing a decisive test of the electroweak baryogenesis scenario – a new setup with a much improved intrinsic sensitivity is needed. The n2EDM is designed to meet this requirement with a foreseen statistical precision 5 times better than the RAL-Sussex apparatus. Combined with the current performances of the PSI UCN source, a limit of $4 \times 10^{-27}\,e\,\mathrm{cm}$ could be achieved after 4-5 years of data taking, *i.e.* in about 10 years. Assuming the UCN source will reach its nominal performances, the $10^{-28}\,e\,\mathrm{cm}$ range will start to be explored. This goal is shared by all other collaborations, both in terms of sensitivity and planning. A clear advantage of our collaborative effort is, however, that we have a running and very well performing system at hand. This includes the possibility to continously improve and test future options while implementing tested solutions for n2EDM.

In conclusion, we beleive our collaboration has a well-defined program to reach the ambitious goal of decreasing the current limit on the neutron electric dipole moment by an order of magnitude in the next 10 years. The first steps towards the construction of a new setup have been taken recently by the nEDM@PSI collaboration. In order for the French laboratories to fully contribute to this endeavor, a clear support from the IN2P3 Scientific Council is required in a near future.

References

[1] C. A. Baker *et al*, Phys. Rev. Lett. **97**, 131801 (2006).

[2] M. Pospelov and A. Ritz, Annals Phys. **318** 119 (2005).

[3] A. Ritz, talk at the PSI2013 workshop.

[4] D. McKeen, M. Pospelov and A. Ritz, Phys. Rev. D **87**, 113002 (2013).

[5] D. E. Morrissey and M. J. Ramsey-Musolf, New J. Phys **14**, 125003 (2012).

[6] J. Kozaczuk *et al*, Phys. Rev. D **86**, 096001 (2012). T. Cohen *et al*, Phys. Rev. D **86**, 013009 (2012).

[7] S. J. Huber, M. Pospelov and A. Ritz, Phys. Rev. D **75**, 036006 (2007).

[8] K. Bodek *et al*, NIMA **597** (2008)222-226.

[9] G. Pignol et S. Roccia, Phys. Rev. A 85, 042105 (2012).

[10] D. Ries, Status of the source for ultra cold neutrons at PSI, workshop PSI2013 (2013).

[11] M. Fertl, PhD thesis to be published, PSI and ETH Zurich.

[12] C. Crawford and G. Quéméner, private communication.

[13] J. M. Pendlebury et al., Phys. Rev. A. 70, 032102 (2004).

[14] nedm.web.psi.ch/EDM-world-wide

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