HARD

HEMT Amplifier Research & Development

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Project goals

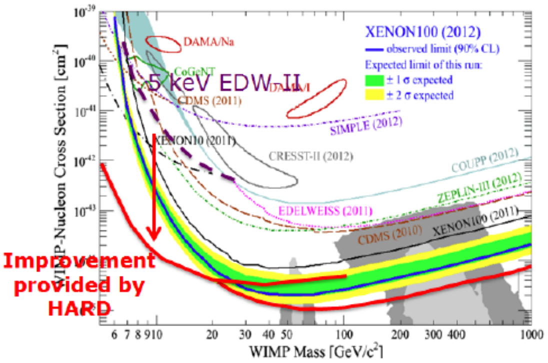

Figure 1 - Status of the direct search for WIMPs (spin independent interaction) and impact of HARD at low WIMP masses.

The main purpose of HARD is to provide EDELWEISS III (and in prospect EURECA) with an improved sensitivity to particle Dark Matter candidates (WIMPs) in the low-mass region. This goal is timely in the international context, since no other experiment will be able to explore this part of the parameter space at the level here envisaged in the next three years. In order to achieve this ambitious result, a new cold front-end electronics is mandatory, which will be designed and developed in the present programme. The conventional cold JFET will be replaced by a low-noise High Electron Mobility Transistor (HEMT), capable to provide a noise reduction by a factor 3, followed by a complete amplifying circuit placed at 1 K. This upgrade will concern a few EDELWEISS-III readout lines. To fully exploit this improvement, a new detector conception is proposed in view of EURECA, aiming at a lower intrinsic capacitance of the readout electrodes of the ionization channel. A cryogenic test facility will be developed for the HARD program, using an existing novel liquid-free dilution refrigerator located at the IRAMIS/SPEC laboratory. In this facility, we foresee a systematic characterization of HEMTs produced custom at LPN, the development of full amplifiers based on these components and their integration with the improved detectors, in view of their installation and test in the Laboratoire Souterraine de Modane. The cross-section sensitivity to WIMPs in the mass range 5-10 GeV will be improved by at least 2 orders of magnitude (Fig. 1), increasing dramatically the discovery potential of EDELWEISS III and setting the bases for a better detector technology for EURECA.

Description of work achieved

During the first 1.5 year of the HARD project, 4 main issues have been accomplished:

<u>HEMTs production at LPN:</u>

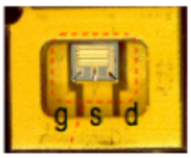

Figure 2 – HEMT in its SOT23 holder.

New HEMTs have been produced for the HARD programme. They are based on an AlGaAs/GaAs heterostructure grown by MBE (Molecular Beam Epitaxy). It consists of a GaAs buffer layer, a 20 nm AlGaAs spacer layer which is much thicker than that employed in commercial HEMTs (between 2 and 5 nm), a Si d-doping layer, then a 15 nm undoped AlGaAs barrier layer, and finally a 6 nm undoped GaAs cap layer. HEMTs with various gate lengths and gate widths are fabricated and individually packaged in a ceramic SOT23 as shown in Fig. 2.

It has to be underlined that HEMTs have no operating temperature limit and their power consumption can be as low as 30 μW. Their voltage noise is almost inversely proportional to the square root of the input capacitance: a noise value as low as

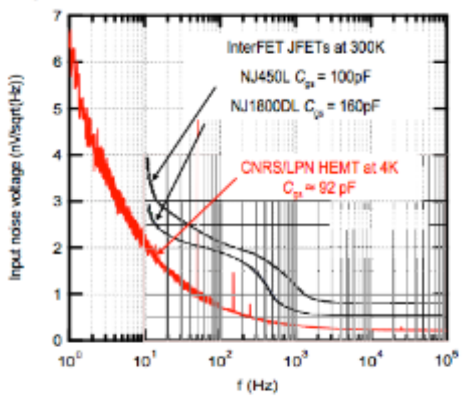

Figure 3 – Comparison between JFETs and HEMTs in terms of noise spectral power.

0.46 nV/√Hz at 1 kHz has been obtained with an input capacitance of about 100 pF (Fig. 3). The 1/f noise that was penalizing HEMTs for low frequency applications has been dramatically reduced and becomes negligible above 1 kHz. Preliminary results show a very weak dependence of the HEMT input noise on its gate impedance, which is a very promising result for realization of charge amplifiers. These transistors are therefore very suitable for high impedance low-temperature detector.
A dedicated HEMT production for the HARD project with a capacitance of 200 pF will start in the coming months.

Production and test of a new amplification board @ IRFU/SEDI:

Figure 4 - Picture of the CRYOHARD amplifier board.

A new voltage amplifier board capable to read 4 ionization channels and 2 heat channels has been produced and tested at 4K by the SEDI group involved in the project, coordinated by Xavier de la Broise.
The board prototype, named CRYOHARD, is supposed to be connected on one FID EDELWEISS detector at the 1K stage of the LSM cryostat.
The main characteristics of this amplifier board are :

- Very low operation temperature, down to ~ 1 K.
- Very low noise. The amplifier noise will be as close as possible to that of the input HEMT, i.e. 0.5 nV/√Hz and at 4.2 K, with a gate-source capacitance Cgs=100 pF.
- High input impedance, optimized for low-threshold charge collection. (The amplifier input capacitance will be proportional to that of the input HEMT with a proportionality factor between 1 and 0.2.)
- Band-width: from DC to ~ 20 kHz.
- Very low power consumption: of the order of 1 mW/channel.
- Gain: between 10 and 100, and temperature-stable in time (~ 1%)

All these properties have been matched during a recent test done at IRFU/SEDI where the amplifier board has been tested inside a LHe dewar.
Fig. 4 shows the produced CRYOHARD amplifier board.

Above-ground tests @ CSNSM

Many tests have been done at CSNSM in order to characterize HEMTs in terms of noise performances.
We have started with a comparison of different gate geometries and we have moved to a direct comparison between HEMTs and a JFET used in the present EDELWEISS bolometer read-out.

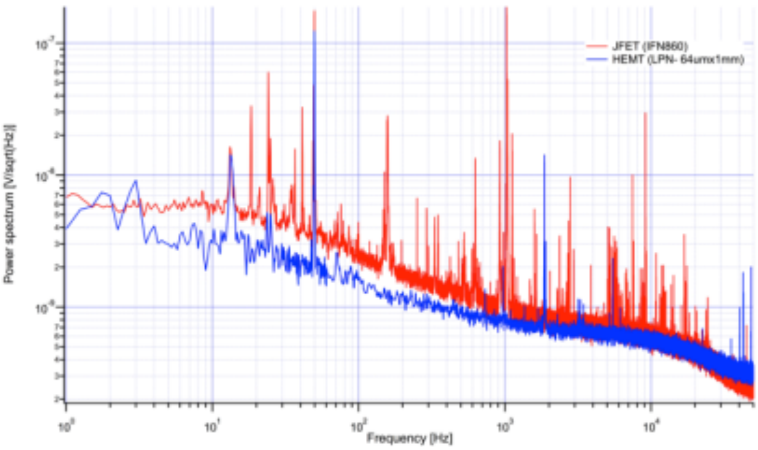

Figure 5 – Noise power spectrum : JFET vs. HEMT @ CSNSM.

Fig. 5 shows this comparison: the noise is 6 nV/sqtr(Hz) at 10 Hz for the JFET and 3 nV/sqtr(Hz) for the HEMT.
The capability to reproduce noise condition compatible with those presented by Jin Yong and collaborators was an important step in the comprehension of these devices.
We have also started few tests on a simplified board coupled to a real EDW detector. For the moment we are facing an extra-noise and we are working on its understanding.

Development of a new test facility @ IRAMIS/SPEC

Thanks to HARD fundings, we have been able to instrument the Helium Free Dilution Refrigerator at the Cryogenic Lab of IRAMIS/SPEC. We have equipped it with 6 complete temperature channels with temperature regulation (MM3, MGC3), and we have also installed a vibration insulator system (Newport, auto-leveling). The cryostat exhibits 200 μW at 100 mK and cools down in 15 hours from room temperature down to 20 mK (base temperature being about 10 mK). One advantage of this installation is that it can run several ionization and heat/light composite bolometers thanks to the large number of reading channels. The acquisition system was also developed in the P2IO framework. In the coming months this installation will be used as a test-bench for new bolometer prototypes and hot/cold HEMT-based electronics. Once the HARD programme will be finished, this installation will be very useful for further cryogenic tests for astroparticle physics in general. This will be a major valorization for the follow-up of this project.

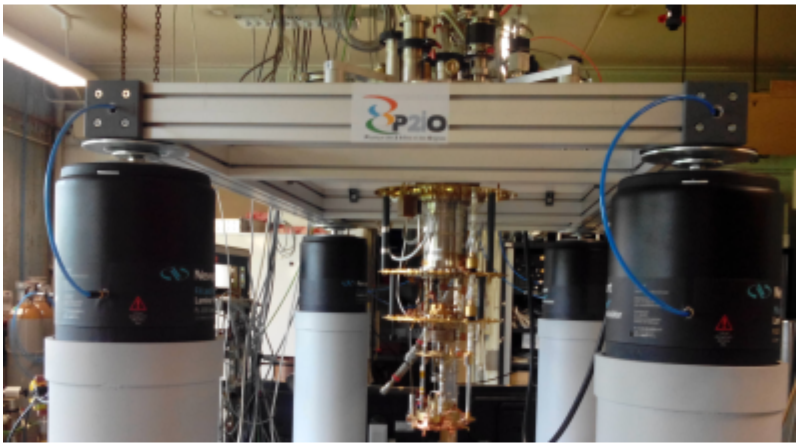

Figure 6 – New cryogenic test facility realized thanks to the HARD project at the Cryogenic Lab of IRAMIS/SPEC.

Next steps :
In the next 1.5 year we will focus mainly on :

- Fabrication of a dedicated FID 200g detector to be tested coupled to the CRYOHARD amplifier board;
- Integration of the detector coupled to the amplifier board in the IRAMIS/SPEC set-up;
- Transfer of this technology to real-size EDELWEISS bolometers in the LSM set-up;

In conclusion, the HARD programme is on schedule.

Publications

- "Cryogenic ultra-low noise HEMT amplifiers board", Xavier DE LA BROÏSE and Ayoub BOUNAB submitted to NIMA, in the framework of the proceedings for the 7th NDIP conference (July 2014).

- The HARD project has been presented by C. Nones with a dedicated poster at the WOLTE10 conference - 10th International Workshop On Low Temperatures Electronics, October 14-17, 2013 Paris, France.

- We foresee to present results at the next LTD conference, which will be held in Grenoble in July 2015.

Relevance of the project within P2IO and specific added value for P2IO

Dark matter is one of the main themes of P2IO, being related to the Universe history and the evolution of its large structures, nowadays a key research topic at the international level. Two P2IO laboratories (CSNSM and IRFU) take part to the EDELWEISS experiment for the direct detection of Dark Matter while Front-end microelectronics is a significant asset of the P2IO laboratories.
In particular the HARD programme strengthens the already existing cooperation among groups at CSNSM, IRFU/SPP and IRFU/SEDI, in the framework of EDELWEISS. But it extends this collaboration to new researchers belonging to IRFU/SEDI, establishing a new synergy which is already giving its fruits.

As a specific added value for P2IO, we can clearly say thay the first observation of an energy threshold of 3 keV in heat-ionization detectors would warrant publication in wide-audience refereed journals and magazines. It would also trigger technology transfers between the European and the American collaborations, with a highlight on EDELWEISS as a leader in its field. This will give a big visibility to P2IO. In addition this work is a good example of synergies between laboratories involved in different Labex. In fact, IRAMIS/SPEC and CNRS/LPN belongs to the PALM Labex, more oriented to nanotechnologies and solid state physics, also at very low temperatures. The HARD programme shows how these competences can be useful and suitable to applications in the astroparticle domain.

Possible valorization of the project

The first immediate outcome of the HARD project is the substantial improvement of the EDELWEISS sensitivity. In prospect this study will be very useful for bolometric dark matter experiment such as EURECA and SuperCDMS. The two collaborations thanks to this programme are already sharing some ideas for further common developments. The knowledge acquired in the HARD project can be also the starting point for the improvement of the heat channel in bolometers in terms of energy threshold. In particular, as a follow-up of the results obtained for the ionization channel, a new development based on the use of BiHEMTs (in view of a differential amplifier) would be possible. The improvement of the heat channel performance can impact also on other cryogenic rare event searches, such as the search for neutrinoless double beta decay with bolometers. In this context thanks to HARD, a collaboration has started with Gianluigi Pessina (INFN-Milan Bicocca).
Furthermore, developments of HEMT-based cold front end electronics, in particular with high-input impedance, low frequency and low noise amplifiers, will find applications in many fields of research outside the detection of rare events. An important example is related to the activity of the group lead by C. Pigot in IRFU/SaP, which will benefit of HARD. There are also some technological applicative fields: HEMT electronics will be of interest for X-ray spectroscopy dedicated to high resolution material analysis. The same is true for magnetometry, either in space or for ground applications, such as medical applications like MRI. Use of HEMTs can be envisaged also in fields like electron Scanning Tunneling Microscope (STM) and related techniques like STP (Scanning Tunneling Potentiometry), when performed at low temperatures.

Expenses

Institution	Total money	Spent (31/10/14)	Items
LPN (through SPP)	15000	0	HEMT production at LPN
IRFU/SPP	25000	15000	Equipment for the new cryogenic installation at IRAMIS/SPEC
IRFU/SEDI_1	8000	8000	Board amplifier production/ LHe for tests
IRFU/SEDI_2	12000	11000	Production of new electronics for bolometric read-out/ Power supply boxes for HEMTs
CSNSM	16000	6000	LHe for tests

Due to some unexpected delays in HEMT production, the 15000 keuros foreseen to pay the components have not yet been transferred to LPN.
The total money spent uo to now (31/10/2014) is about 40 keuros. 15 keuros are already blocked to pay HEMTs while the remaining 20 keuros will be used in the coming months to complete the programme.