DTP International Review Committee

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Review Report of KEK Detector Technology Project

KEK Detector Technology Project (DTP) was started in 2005 to support horizontal efforts to develop common key technologies for the advanced sciences in KEK. The DTP is also expected to diversify its R&D efforts for the benefit of related communities.

The charges of the review committee is

- to comment on the motivation and the aim,
- to evaluate the efforts and the achievements so far,
- to suggest possible/necessary improvements
- to guide proper direction for future

for each project, and

- to comment on the selection of the projects
- to suggest better organization and operation

for the DTP office.

The committee's findings and recommendations for DTP office and common issues are summarized first followed by reports for individual projects.

General Findings

The committee is impressed by the great progress made by the R&D efforts promoted by the KEK DTP. The committee applauds that Silicon-On-Insulator (SOI), superconducting detectors (SCD), FPIX, application specific integrated circuit (ASIC), and CO_2 cooling are developed with specific applications in mind. In particular, the SOI project made extensive efforts to broaden interest in SOI technologies and attract participants outside of the particle physics community, including members of the astrophysics and photon science communities as well as international participants from the US, Poland, Italy, Germany, France, Russia and China.

We are pleased that the local and external recognition of the importance of detector technology has improved by the formation and performance of the DTP division. We are impressed by the many collaborations in DTP among ASIC, SOI, and SCD, which is certainly stimulated by being located in the same DTP unit. Especially, the DTP division has created synergy by having the SOI and SCD groups share the clean room and measurement facilities. There are also many collaborations with universities, which demonstrates that the DTP plays an important role in KEK to function as an inter-university institute.

Concerns and Shortcomings

The committee is impressed by the significant progress made by the DTP projects since the DTP division is formed in 2008. However, we were concerned with general lack of clear goals, resource management and associated development plans for each project. We understand that the DTP office supports generic R&D efforts that are not aimed at specific applications, which makes it difficult to set clear goals. Unfortunately, the lack of clear goals may be responsible for the lack of clear development plan in some projects. On the other hand, some projects are mixing up DTP efforts and efforts for specific applications.

The committee is also concerned with selection and resource allocation procedures of DTP projects. It appears there is no clear policy for these procedures. The steering committee includes many project leaders, which creates an appearance of conflict of interests. In addition, the steering committee may not have sufficient expertise to execute such functions effectively and reliably.

It appears there is no specific plan for technology transfer (and outreach). Useful development might not be properly utilized without proper outreach and technology transfers.

Recommendations

As expressed above, the review committee is concerned both with lack of clear goals for each project and with insufficient project management. With a view to improving these aspects, we make following recommendations:

- The DTP office should set up a project selection committee that includes external experts with clear selection policies. The selection should be based on a critical evaluation of the expected output, timescale, and resources. The possibility to attract external funding is should also be considered. One possible form of implementation would be that the DTP office invites proposals from the community every year, and puts priorities between new proposals and existing projects together with a selection committee.
- The DTP office should work with each project to set objective goals with a total budget and development schedule. (No need to set yearly budget since we understand it is not possible.) Project goals should be formulated to be beneficial for possible applications without too specific to certain applications. Resource allocation (mainly budget) should be made based on annual project reviews. Each project should be evaluated before continuing beyond the initial term and budget.

- The DTP office (and/or KEK management) should allocate human resources for outreach and technology transfer. (KEK may take advantage of existing infrastructure for such activities.)

Response from KEKDTP

At the initial stage of the DTP startup, we did put significant effort to keep the R&D activities in DTP generic and independent of any specific actual science projects as much as possible to extract maximum cooperation among the projects including the fields of HEP, NEP, photon science, neutron science and so forth. We agree some DTP projects might show "lack of clear goal" because of this initial goal.

DTP is now in the next stage after establishing some of the initial goal such as the local and external recognition of the importance of detector technology and should be ready to encourage the projects to focus on several definite goals, which would be evaluated by the selection committee with external members. It is noted, though, that the committee should consider not only on which is the best planned proposal to realize but also what is the direction most necessary to KEK and the related communities.

As for the lack of human resources, KEK has provided one professor position devoted to DTP from March 2013. Thus we have a well-experienced expert on semiconductor technology in the position successfully. He has been working long to develop and apply the SOI technology to radiation sensor in OKI semiconductor. We expect he would play a leading role in not only developments of the technology and also applications for industrial use.

Comments from committee

The committee believes objective goals and schedule can be set even for generic development without associating with any specific projects.

Silicon on Insulator (SOI)

General Findings

The SOI technology is an emerging technology to realize pixel detectors with high functionalities since it can realize CMOS circuits integrated with the fully depleted detector in a monolithic form. One of the main objectives of the SOI development is to solve the back gate effect where the bias voltage applied to the detector affects the properties of MOS FETs. Once the back gate effect is resolved, the SOI technology has the great potential to be used in several applications: high-energy physics, X-ray detection and others. This first 5 years have produced proof of principle of the technology and it now looks mature to be implemented in some applications as radiation detectors.

The group has demonstrated that the back gate effect can be mitigated by a buried P-well implant with some side effects. A new technique employing a double SOI wafer is in progress to increase immunity for a radiation dose, and to prevent the digital activity to interfere with the sensing volume.

The group has demonstrated full depletion of a significant fraction, estimated 170 μm, of a 500 μm float-zone handle wafer. This is enough for close to 100% absorption of X-rays at low energy range as well as for the detection of Minimum Ionising Particles with good S/N ratio.

The group has also demonstrated it is possible to manufacture stitched sensors, although no result was presented[SOI-1].

Good international consortium has been established. The KEK group manages two MPW runs per year and, in 2013, it has reached its 10th run. Participants come from Asia, Europe and America, demonstrating the reach of the technology.

The support from the foundry (LAPIS Semiconductor) seems to be very good, with commitment for continuous improvement of the technology.

Concerns and Shortcomings

Leakage current remains still a serious limitation for spectroscopic use. It is of concern that the origin of the higher leakage current has not been understood[SOI-2].

With about 40 masks, this technology is fairly complex. Although this level is not unique in microelectronics technology, it is of concern, especially for the large area sensors that many applications would require. Also, LAPIS is only now starting building its expertise in stitching. The sensor manufactured so far only employs one-dimensional stitching and with fairly large (10 μm) buffer regions. This is not state-of-art, and, while there should be no showstopper to achieve state-of-art stitching, this would require further developments at the foundry[SOI-3].

While the support from LAPIS is certainly exceptional, this SOI technology remains restricted to a single vendor. As LAPIS is a commercial organization and every project needs ultimately to find an economic justification, it is not clear what this justification is or if there is any sound one. The SOI group has built an exceptionally good relationship with the foundry, but for longer term stability it would seem important for the relationship to have a sounder financial justification, i.e. through the start of production for at least one sensor in one application. In the fast paced field of microelectronics, where companies can change focus or disappear, the single vendor relationship is a major risk and concern[SOI-4].

The SOI group is understaffed, with a limited access to professional microelectronics designer (most of the work is done by students or post-docs). This is particularly worrying now, where the project should shift its focus from technology development to design of full size prototypes. This would require a level of expertise in microelectronics design which requires years of experience. Retention of staff is a problem as this prevents the group from reaching critical mass. To this respect, it is also not beneficial that the communication between the SOI and the ASIC group is non ideal. It is also not clear if design reviews are routinely made[SOI-5].

The first 5 years were instrumental in developing the technology. It is now time for the consortium to apply the technology successfully in some real applications. For this, we think it would be beneficial for the group to place more efforts on the most promising applications, identifying 'low-hanging fruits' and then building a portfolio of applications.[SOI-6]

Recommendations

Stitching is of major importance for many scientific applications. The SOI group should clearly demonstrate stitching at LAPIS works fine and also complete the development of this module by demonstrating 2D stitching is possible and achieving smaller buffer regions[SOI-7].

In order to share common design techniques and also to avoid common errors, design reviews should be held for all SOI submissions with wide audience[SOI-8].

The group should also try to reduce the risk associated with the single vendor and try to establish if it would be possible to have a similar technology with another vendor. In order to retain LAPIS and attract more vendors, the SOI group should focus on designing at least one sensor that could be used for a real application. It should work on identifying early winners, more than trying to demonstrate the technology for any possible applications. By doing this, it could be useful for the consortium to do a more in depth review of other technologies, in order to identify in which applications the SOI technology would be the optimum technology. It should be noted that CMOS Monolithic Active Pixel Sensors (MAPS), have made progress and benefit from a larger support from industry[SOI-9].

If it hasn't been already done, it would also be beneficial for the project to define the allocation of resources and draw a plan for the next 5 years, with a higher level of details for the first 2 years. The SOI group should be reinforced with the addition of professional microelectronics designers. Communications and collaborative work with the ASIC group should be increased. Design reviews jointly held by two groups could be the good first step[SOI-10].

Response from the group

SOI-1: Although the yield of the stitched sensor is not yet so good, there are many stitched sensors working well.

SOI-2: Leakage current changes depend on the wafer manufacturer and lots. Number of manufacturer for the 8" FZ wafer is not so many, and we will try to find the best wafer supplier. In addition, we will continue to study structure of backside and bonding surface etc.

SOI-3: Now the yield of the small sensors is relatively high, so we don't think the present number of masks is critical. Of course, it is better to reduce the number of masks, but it needs large re-works and causes other confusions. However, as for the large sensor which needs stitching, we should re-define Design Rules and establish method to repair faulty circuits.

SOI-4: JAXA, Japan Aerospace Exploration Agency, is another main user of the Lapis SOI process. Keeping the radiation hard electronics parts is primary concern of the JAXA. Thus JAXA and KEK are asking Japanese government to identify the SOI process as a one of the critical technology to keep in Japan. Of course, we will work hard to develop SOI sensor which can be sold commercially.

SOI-5: We will continue to ask KEK management to increase our staff, but it looks very hard seeing present status of KEK. We are expanding SOI collaboration to many Universities and Laboratories where LSI experts exist.

SOI-6: Yes, we agree.

SOI-7: We think our first priority is to complete a sensor without the stitching. Thus the development of the stitching technology is low priority for the moment.

SOI-8: Yes, we agree.

SOI-9: Yes, but we are a group that started later in pixel detectors and have less staff. Then it is our strength that we can use the Lapis process and their expertise like as our laboratory facility. We would like to make use of this merit as much as possible.

SOI-10: Yes, we try to do.

Comments from committee

Regarding SOI-9, the committee's intention was to identify suitable applications for the SOI technology by a in depth review of other technologies.

Micro-Pattern Gas Detector (MPGD)

General Findings

The development of MPGDs fits within the mission of KEK for conducting research with quantum beams, such as electron, photon, neutron, and muon beams because an MPGD is utilized in neutron science and photon science conducted at J-PARC and the PF. The KEK DTP has developed a neutron detector using a boron-coated GEM and a hard X-ray detector using a gold-plated GEM. It is notable that for neutron science, the DTP has demonstrated a nice TOF measurement with 2D position resolution to resolve the microscopic lattice structure in a bulk material instead of only a thin slice of the sample as with X-ray. The boron-coated GEM is expected to be widely used in the community.

The collaboration in the DTP on the development of an ASIC and readout electronics for MPGDs demonstrated that KEK has the best capability to develop the radiation detectors efficiently. After the previous review, a working group was formed by KEK, universities, and other research institutions for not only sharing information on development and experience but also conducting basic R&D of MPGDs. It is noteworthy that this group is developing MPGDs with more robustness against discharges by using resistive materials and resistive electrodes, though further testing and development are necessary. Their achievements have become more widely known through international conferences and among the RD51 collaboration at CERN.

Concerns and Shortcomings

The current achievements are valued in general. However, the future roadmap is vague. For example, in the oral presentation, it was expressed that the pixel readout will be developed some years later. The detailed applications and their specifications were not shown[MPGD-1].

Concerning the hard X-ray detector using a gold-plated GEM, a fine position resolution is obtained thanks to the MPGD. However, lower efficiency compared with other technologies is a problem for practical uses such as medical applications[MPGD-2].

To share the information on development and experience in the community could accelerate the development. As described above, the DTP formed a group with researchers at other institutions. However, it is unclear whether the DTP collaborates with MPGD R&D groups for upgrade of projects in operation or future projects such as ILC. If not, such collaboration would create a synergy effect[MPGD-3].

Recommendations

Since the DTP has fewer resources than what DTP members would like to do, the goals of the project should be carefully chosen and focused. The presented roadmap seems to be based only on personal intention. It is recommended to have a logical and reasonable roadmap to get external budgets and attract young students and postdocs. Applications should not be chosen from only the point of view of advantages over existing detectors. Disadvantages should also be considered after clarifying the specifications and requirements for practical uses. Advices from professionals in the corresponding fields would be helpful for choosing applications and determining development goals with consideration of usefulness[MPGD-4].

The developed MPGDs are suitable to be used in the fields of neutron science and photon science. It is recommended that the DTP should collaborate further with scientists from these fields and the developed MPGD should be commercialized. For commercialization of products, the KEK management should support the DTP by securing the adequate number of office staffs at the department of industry-KEK cooperation or work with RIKEN since they have experiences to commercialize neutron detectors[MPGD-5].

As mentioned above, a working group formed by the DTP, universities, and other research institutions is achieving nice results on an MPGD with more robustness against discharges. The KEK management should continue to provide financial support for their activities[MPGD-6].

Response from the group

MPGD-1: More efforts will be done to make R&D strategy clear.

MPGD-2: We hear the comment sincerely and will consider how to proceed with this R&D.

MPGD-3: Sharing the information with other groups has been done in various occasions, yearly domestic workshop and other small meetings. More efforts will be done as one of activities of MPGD R&D groups.

MPGD-4: More efforts will be done for getting advices from other professional people to proceed with MPGD projects.

MPGD-5: We have collaborated with some companies for the commercialization. The developed ASIC chips and readout boards are commercially available. The company has sold the neutron beam monitor, also. More products are followed. The recommendation is helpful for our moment.

MPGD-6: We are encouraged to continue developing new MPGD with more robustness against discharges.

Superconducting Detector (SCD)

General Findings

Superconducting detectors (SCDs) provide unique sensing capabilities such as photon-noise limited detection of millimeter waves, energy-resolving detection of visible light, high energy-resolution of X-rays and particles and most sensitive searching capabilities for dark matter because superconductors require a lower excitation energy (typically 1/1000) compared to semiconductors. Development of SCDs at KEK is expected to contribute also to related scientific disciplines, such as astronomy/astrophysics and superconducting electronics.

Development of SCDs in KEK is very important and should be encouraged since SCDs will become increasingly critical to the high-energy physics; KEK has correctly articulated this point, by for example the timely initiation of the LiteBIRD program to explore the high-energy state of the early universe. This mission capitalizes on the rapid growth in the number of pixels in superconducting detector arrays, which now exceeds 10,000 detector elements and continues to grow. LiteBIRD also provides a unique opportunity to the worldwide SCD community, because it is one of the very few proposed observatories (along with SPICA) with an actively cooled primary mirror, where ultra-sensitive SCDs with noise equivalent powers (NEPs) below 10^{-18} W $Hz^{-0.5}$ are required.

The SCD group focuses on two kinds of superconducting detectors, microwave kinetic inductance detectors (MKIDs) and superconducting tunnel junctions (STJs). This is an interesting combination because both of them can be used as pair-breaking quantum detectors, and much of the underlying physical processes are common. For example, the ultimate sensitivity of both detectors are set by the generation recombination (G-R) noise of quasiparticles, unless the G-R noise is made lower than the photon noise. The two detectors probe the density of quasiparticles in a different way, and therefore by having the two technologies side-by-side in the laboratory could provide a complementary diagnosis of the device behavior. This should be helpful in improving their performance.

Concerns and Shortcomings

The committee acknowledges that the SCD group are eager to, and capable of, coming up with their original ideas, instead of simply following what has been demonstrated by other groups. However, we also feel that some members may be overconfident and reluctant to learn from previous developments, which may have negative effects on the realization of a functional detector unit with competitive performance. Publishing in peer-reviewed journal provides a good way to keep in touch with the external world.

In our view, the group makes the step from a new idea to device fabrication too quickly. To give a few examples:

- Lack of end-to-end system consideration
  Example: STJs for infrared waves have been developed, without a conceptual idea of how to couple light into the detector with sufficient quantum efficiency.
- Lack of contact with the broader community of the subject
  Example: A rather new kind of readout scheme for mm-waves MKIDs has been developed, based on a misunderstanding of the conventional scheme. This effort could have been avoided if the group had been communicating with any group in the world with experience in MKIDs.
- Lack of evaluation planning on the devices being developed
  Example: Many different kinds of MKIDs have been fabricated, but the advance in understanding is relatively poor (or at least not presented). This includes the beam pattern of the sinuous antenna and log-periodic antenna, the band-pass characteristics of the filters, optical efficiency and so on.

Recommendations

We recommend introducing following steps before starting to fabricate chips in the clean room:

1. Survey of existing technologies
   We recommend a more careful technology survey of available and competitive technologies in Japan and in the world before starting the project and during the project.
2. Conceptual design phase
   End-to-end system evaluation should be made based on a conceptual design to identify potential risks and reduce the amount of unnecessary efforts for the final product. This information is also essential to evaluate the feasibility of the instrument itself.
   The conceptual design should include rough calculations and simulations of the expected performance.
   Design reviews should be conducted with experts from outside the SCD group with various expertise before the fabrications.
3. Prototyping phase
   Before fabricating devices, careful evaluation plans and milestones should be developed. It usually helps to design experiments in such a way that each component can be evaluated independently (e.g., band pass characteristics of the antenna and filters.)

We recommend DTP office (and KEK) to increase their support to the development of SCDs, along with other DTP activities. In particular, it is essential to assign dedicated scientific and technical staff to the currently understaffed development of SCDs, in order to bring the technological level up to where the SCDs developed by KEK can be considered as serious candidates for missions such as LiteBIRD.

We recommend the SCD group to strengthen their interaction and collaboration with local (TIA-Nano and related institutes in Tsukuba), national (e.g., NAOJ, RIKEN, JAXA, and universities), and international (USA, Europe) institutions.

The SCD group obtained maximum internal resonator $Q=10^6$ and dark $NEP=10^{-17}$ W $Hz^{-0.5}$ at 0.3 K with MKIDs for CMB Observation. Device fabrication has been successfully improved. We would recommend to evaluate the followings quantitatively:

1. Whether the experimental performance obtained at the present stage is sufficient from the viewpoint of the final goal and the rest of the project.
2. Expected improvement in NEP by replacing Al with TiN and thereby decreasing the volume of the kinetic inductance elements.

Detecting alpha particles through phonons using the substrate as the absorber is interesting. Though we understand the proposal to use lumped MKIDs for increasing the sensitivity, is it not clear if this is the only way to achieve the performance goal. We recommend to check quantitatively whether the present sensitivity experimentally obtained agrees with the theoretical prediction when taking into account of the ratio of volume (or surface area) of Al sensors and the substrates.

A distributed STJ is interesting for wider band operation than parallel-connected twin junction (PCTJ) because the input impedance is in principle independent of frequency. However, resonant behavior was presented, indicating the frequency-dependent coupling between the distributed junction and the antenna. In addition, a quantitative comparison of experimental bandwidth between distributed STJ and PCTJ has not been carried out. This does means that the advantage of the distributed STJ has not been verified. We would recommend evaluating the reason of this resonant regime and how to increase the bandwidth up to the expected value.

It is interesting to develop the integration technique of STJ on SOI. However, it is not clear whether the noise and power consumption of MOS transistors on the SOI meet the requirement of the target system. We would recommend evaluating whether this approach is suitable.

Response from the group

We are very happy to see that the committee recommends DTP office (and KEK) to increase their support to the development of SCDs. We also appreciate that the committee thinks it essential to assign dedicated scientific and technical staff to the currently understaffed development of SCDs, in order to bring the technological level up to where the SCDs developed by KEK can be considered as serious candidates for missions such as LiteBIRD. In the following, we give our reply to each comment of the committee.

First, we recognize the importance of interacting with other groups that are also developing SCDs. This review was a good opportunity for us to become acquainted with the reviewers and to interact with them for technical issues. We hope to continue interacting with a wider community, both domestic and international.

Secondly, in the international review, we admit that our presentations should have included more quantitative discussions. For example, the quality factor and NEP values obtained by our group were not proved to be sufficient for the final goal for high-precision experiments such as LiteBIRD. For the MKID design that employs Al side deposition, we are now discussing its sensitivity more quantitatively along with the preparation of replies to reviewers of a paper we have submitted. Please note, however, that the LiteBIRD working group includes the UC Berkeley group who has been developing a wide-band receiver with the sinuous antenna and the band-pass filters for multichroic millimeter-wave detection for the POLARBEAR-2 experiment.

Although the group uses TES bolometers, we think we will be able to apply the similar technique to the MKIDs.

Third, for phonon detections with lumped-element KIDs (LEKIDs), we have recently confirmed that the LEKIDs have a better phonon sensitivity than the quarter-wavelength KIDs. The improvement of the sensitivity is found to be comparable to the expectation obtained by taking the ratio of the sensitive areas of the two types of KIDs. As for the distributed STJ, we have designed the antenna-coupled STJs so that they have frequency-dependent coupling; such design could be applied to the multichroic detections with frequency filters. The bandwidth of the distributed STJ is expected to be comparable to that of PCTJ. Details are given in the Doctoral thesis written by Satoru Mima (written in Japanese). He observed the bandwidth that is a few times wider than the expectations. He suggested it was due to multi-tunneling. We feel we need further investigation to confirm that.

As for optical coupling between STJ and far infrared photon, an Infrared photon from cosmic background neutrino decay will be received by a reflecting telescope with a main mirror of 15 cm diameter and 1m focal length, which will be loaded onto a research rocket, and transmitted to an array of STJ pixels on the focal plane via collimators, secondary mirrors, band pass filters and a diffraction grating device which covers the range from 40 μm to 80 μm in wavelength and distributes photons into 50 STJ pixels per 0.8 μm. Each STJ pixel is supposed to have 100 μm x 100 μm sensitive area to receive and detect an infrared single photon. Currently we are measuring the quantum efficiency of Nb/Al-STJ by illuminating a laser pulse of a known number of photons at single photon level in visible (470 nm) and near infrared (1.3um) regions. We are establishing the principle of the quantum efficiency measurement of Nb/Al-STJ for visible photons, and targeting the measurement for middle infrared (10 μm) photons as a next step. We are considering conceptually the same techniques as anti-reflective coating with commercially available dielectric film of the desirable thickness to improve the quantum efficiency. Similar techniques are widely used for anti-reflective coating of infrared lenses for astronomical observation fields.

As for SOI-STJ noise and power consumption issues, we have started noise measurement using proto-type modules of SOI-STJ and we are also working on the circuit design improvement to reduce the power consumption per channel from a few μW to sub μW order.

Noble Liquid Time Projection Chamber (LTPC)

General Remarks

Noble liquid TPCs are attracting much attention since they provide tracking and calorimetry with high density and large volume (mass). They have high potential for experiments involving weakly interacting particles such as neutrino and dark matter.

An astonishing aspect of R&D for noble liquid detectors is that small systems are nearly as complex as large systems. They require a complex infrastructure for cooling to cryogenic temperatures, purification to sub-ppb level of impurities, charge measurements down to the sub-fC range, and light detection of single photon sensitivity. And these operation conditions have to be stable for extensive time periods, sometimes several months. Given those requirements, the achievements of the Liquid TPC group are quite impressive. A very small group assembled systems that produce some signals. However, there are still many technical issues to be solved or corrected before the full potential of the detector can be explored. Several small and a few large noble liquid detectors are operating in the world, and regular contacts with other groups in the field could significantly reduce the development time and costs[TPC-1].

Since LAr and LXe TPCs are not very different, it might make more sense to focus on one technology now. After establishing one technology, DTP may resume development of the other technology taking advantage of techniques gain by then[TPC-2].

General Remarks for Liquid Xe TPC (LXeTPC)

LXeTPC group aims to develop a LXeTPC that can used for Positron Emission Tomography (PET) systems, taking advantage of three dimensional position measurements of charge signals as well as fast timing signals of scintillation lights and good energy resolution in a compact volume. Since PET is not one of the main interests of KEK, the committee is not convinced whether it is the right goal for the LXeTPC project[TPC-3].

Although much progress has been made, there still are many issues to be solved before practical use. Many of those problems are originated from support system problems that were solved years ago by other groups, and they will take some time and efforts to be resolved due to limited manpower[TPC-4].

It was proposed to replace the PMT now detecting the direct and the proportional scintillation by MPGD in the form of gaseous photo multiplier (GPM). Such a read out would even significantly enhance the benefits of new read out scheme. Bringing the idea even further, it was suggested to immerse the MPGD, GEM or ThGEM, into the liquid. The first observation of proportional scintillation in a liquid filled ThGEM was recently reported from the Weizmann Institute in Israel. This research might lead to TPCs of much larger size, higher performance, and at significantly lower costs. These detectors might then also be interesting for high-energy physics[TPC-5].

Concerns and Recommendations for LXeTPC

The purity problem haunted all liquid xenon developments until continuous purification by recirculation was introduced in the MEG experiment. Looking at other groups, nearly the same components are used, except for the getter pump. And to keep the record straight much of the innovative information concerning recirculation and also cooling originated in KEK. The single most relevant problem is the recirculation rate. It is limited by the available cooling power to 1.2 standard liters per minute (SLPM) because the heat exchanger does not work efficiently. The heat exchanger itself and it's connecting lines have to be well insulated, preferably by a thermal vacuum. This will increase the maximum rate to 5 SLPM, limited by the getter. This subject was discussed with the KEK group 4–5 years ago, but it seems the importance was misjudged[TPC-6].

Unlike many LXeTPCs nowadays, the pulse tube refrigerator (PTR) is mounted directly in the xenon gas. A much better way is to employ a copper cold-finger reaching through the wall of the inner chamber. Only the Oxygen Free High Conductivity (OFHC) copper surface of the cold finger is exposed to the xenon, while the other components, PTR, heater module, temperature sensors, and cables are in the vacuum space. This arrangement also helps with purity since many potentially 'dirty' parts, e.g. the heater module with large epoxy surfaces, does not come in contact with the xenon at all. Mounting the PTR remotely can help to mitigate the future problem of acoustic noise affecting the charge measurement. The high frequency noise stems from the He steaming in the PTR[TPC-7].

There are more minor points, e.g. the Teflon signal cables should have no jacket since trapped air will be released very slowly reducing the purity. After these the set up should allow the study of the xenon detector, e.g. signal response, read out, etc[TPC-8].

There are not many centers globally working on LXe detectors, but luckily most of the groups are very open to discuss technical details. A more intense communication might avoid similar problems in the future. In particular, they should work with other Japanese groups such as MEG or XMASS since detailed communications and site visits are easier. Ironically much innovative information came the other way out of KEK, e.g. the recirculation, the model of the diaphragm pump, the idea to use a heat exchanger, and of course the pulse tube refrigerator (PTR) itself. Furthermore, it might be more efficient to use a proven LXe system as platform for the TPC studies[TPC-9]. Complete LXe test platforms can be acquired commercially, e.g. SHS Vacuum, Shanghai. Four such systems exist so far internationally, and all were operating satisfactorily right from the start. The present system would then be used to explore the aspects of filling, recovery, purification and so on[TPC-10].

The underlying principle of Dual Phase technology is Proportional Scintillation in the gas phase. However, Proportional Scintillation also exists in liquid phase as the Doke group proved 35 years ago. At that time where was no advantage in using this read out scheme, but with technological advances now it seems to be very beneficial for large and very large detectors. Research has started about 3 years ago, after a KEK seminar. The technique is under investigation at Columbia University and SJTU, Shanghai. The major difference to the small TPC at KEK is the charge read out via proportional scintillation light instead of direct charge measurement with integrating amplifiers[TPC-11].

The committee recommends to re-align the LXe project with the recent research in new detector structures and to take advantage of the synergy of the LXe project, the MPGD project, and the ASIC development[TPC-12]. For such a road map, however, the LXe project might have to be reinforced in manpower.

General Remarks for Liquid Ar TPC (LArTPC)

LArTPC group aims to develop a LArTPC that can be used for neutrino and dark matter experiments, which is well aligned with objectives of KEK. The status of the LArTPC project is more advanced and appears more successful. The test detectors show that the technology is mastered, and for some processes the development even goes further with detectors for some special applications. It was a good challenge to upgrade the Ar gas recirculation and the cryo-system to reduce the impurity level. The impurity level is demonstrated 0.3 ppb, from 0.8 ppb.

Concerns and Recommendations for Liquid LArTPC

One of main issues of the project is whether a careful regeneration procedure for the filters is needed. One of the important techniques to be established is how to replace exhausted filters to keep the high purity level in the system[TPC-13].

It is more difficult to foresee the future for this project. Quality control of concrete is not one of the main businesses of KEK. The most likely detector for high-energy or neutrino physics would be a large detector in the 1–10 kton range. It is not clear whether the acquired expertise and experience will be sufficient to develop a detector of this size. Presently the largest LAr detector is the 600 ton Icarus, which is a product of the 1990's technologies. Such large detectors would require completely new technologies since the size of the detectors makes a huge difference. For the cleaning and preparation of surfaces, new methods have to be developed going far beyond the Icarus. The purification and signal read out also have to be adapted for the new scale[TPC-14].

Response from the group

TPC-1: We have communicated to foreign people regularly, however, we will consider the possibility to have other communications (e.g.; Shanghai group) and/or to have deeper communications.

TPC-2: We will also start considering the possibility to have common R&D items between LXe and LAr. In order to do this we pick up the common items at first, and then proceed with them in a timely manner.

TPC-3: Present target depends on interest of researchers involved with this R&D. Other targets such as Dark matter and double beta decay are welcome.

TPC-4: Yes, we have noticed the importance of heat exchanger with vacuum insulation for fast purification.

TPC-5: Thanks for this information. We see that such detection could increase the detection efficiency as well as the cost performance.

TPC-6: Yes, we have constructed a prototype of the heat exchanger a few years ago. But, it has never been operated because of "man power limit". Also, it was pointed out that its location should be moved to top of the cooler by an expert who has such experience at Subatech.

In this fiscal year, we initiated this effort with large modification as presented at this review. The schematic of this system is appended, which has the heat exchanger and the second cooler in a vacuum chamber. Even with this system, liquid Xe could be directly provided.

TPC-7: W agree with the remote location in future. Our next system explained above must be an intermediate stage.

TPC-8: We will replace them by ones with Kaptons which are commercially available as cables for ultra vacuum application.

TPC-9: Yes, we have also developed based on the information. Several members are participating in MEG and XMASS. So, such communication has no problem.

TPC-10: We will consider this possibility in next fiscal year. We would like ask you for the information at the SHS Vacuum, Shanghai.

TPC-11: Apparently, we are very interested. We would like to know more especially the position measurement accuracy in three dimensions.

TPC-12: Yes, there is no problem in such re-alignment in principle if there are enough staffs and interested groups.

TPC-13: We skipped the item in the presentation, but we already established a regeneration procedure with evacuation and H_2 + Ar gas. Thus the regeneration itself is not an issue. If the filters are put in parallel inside the purification system, we can replace the filter after the exhausting easily.

TPC-14: As mentioned during the review, building 1-10 kton level LAr detector is an issue beyond the DTP. (because huge man power and budget are required.) To solve this, laboratory and KEK wide supports are needed.

Ultra Fast Pixel Detector (FPIX)

General Findings

In order to conduct a time-resolved measurement by employing pulsed synchrotron X-rays, the FPIX group has developed a frontend Application-Specific Integrated Circuit (ASIC). The ASIC is fabricated with a 0.8 μm BiCMOS process from NJRC, which is compatible with a Si-APD with 2-ns pulse-pair resolving time. They assembled a 10-ns sampling system with a 64-channel test board together with a 64-channel Si-APD from Hamamatsu Photonics, and tested the assembly with the 8-keV X-ray beam at the Photon factory, KEK. Eventually they successfully demonstrated that the detector could clearly record the time structure of X-rays deriving from the electron-bunch filling of the PF ring. By upgrading the module to a 1-ns sampling system, they have succeeded to distinguish the 2-ns interval of X-rays originating from the electron multi-bunch structure.

Concerns and Shortcomings

They need a new circuit designer for the fast BJT circuit, since the former designer is no longer available. It takes many years to train a circuit designer for a radiation measurement system.

Since the detail of the ASIC was not presented thoroughly at the DTP review, it is difficult evaluate the circuit itself.

The power consumption of the above mentioned ASIC is 0.64 W per chip, which includes only 4 identical signal channels. In order to cope with large number of APD pixels, it requires special cooling devices to remove heat dissipated from the ASIC.

Recommendations

The ASIC could be fabricated with a modern SiGe BiCMOS process to reduce power consumption from the circuit, provided that an adequate designer is available[FPIX-1].

Response from the group

FPIX-1: We will continue to search a new circuit designer and will try to gain a help from a venture company. If we could obtain funds and a new designer for our project, we would introduce a modern SiGe BiCMOS process for ASIC.

Application-Specific Integrated Circuits (ASIC)

General Findings

Demand for ASICs is growing in accelerator science. Twenty-one ASIC development projects have been started in KEK for accelerator science. The ASIC chips that were developed by the DTP projects are actually used for many experiments including those for MPGD, PSD, MPPC, DC and TPC projects. The QPIX project is a currently on-going project to develop an ASIC with TDC, ADC and the LTCC flip-chip technology for gaseous detectors. An important advantage of the QPIX is in-pixel ADC since the commonly used TIMEPIX chip does not have an on-chip ADC.

Increasing the number of researchers developing an ASIC is another objective for the ASIC group. The ASIC group organized ASIC training courses since 2008 and the number of the attendees are increasing from 40 to more than 160. The committee recognizes that this is an extremely important activity to promote the ASIC developments for accelerator science. The ASIC group also provided on the job training for young researchers in the experiments that requires custom ASICs. Eleven projects successfully completed their ASIC developments and ten projects are currently supported by the ASIC group. KEK should continue to support the education and development of ASICs.

Concerns and Shortcomings

Although ASIC development at KEK is very active, KEK should promote ASIC development with extreme performance required for top accelerator science. The QPIX ASIC being developed at KEK is unique and advanced compared with similar developments. However, the performance of the QPIX still requires improvements. For instance, the threshold of the QPIX chip is still high, which limits applications. Future plan presented at the review to improve the threshold should be realized[ASIC-1].

From the viewpoints of ASIC design efficiency and quality, ASIC design environment should be improved. A mixed-signal simulation and design environment should be established to enable development of sophisticated ASICs.

For efficient and fast development of ASIC chips, developments of common IP libraries such as analog amplifiers, ADC, DAC and functional logic circuits are also very important. However, sufficient effort has not been made to promote such activities[ASIC-2].

Recommendations

KEK should continue active roles on the ASIC developments and educations of researchers, particularly, young researchers, and should make more efforts to establish sophisticated ASIC design environment to enable ASIC developments for top accelerator science.

Building closer collaborations between the ASIC and other DTP groups such as SOI, MPGD and TPC are desired for efficient design and advanced performance in ASICs and detectors[ASIC-3].

Response from the group

ASIC-1: Yes, we are/will be doing our best to improve QPIX performance.

ASIC-2: Although we already have amplifiers, DACs and slow ADC libraries on 0.18 μm CMOS process, we understand it is not adequate resource for ASIC development for top accelerator science. We will accelerate development of more sophisticated ASICs and spreading those know-how to young researchers based on successfully launched education activity.

ASIC-3: Yes, we would like to do our best with KEK support.

Two-Phase CO_2 Cooling system

General Findings

Demands for cooling systems have been increasing due to conflicts between higher power consumption and low material requirements of (mostly) vertex detectors. Compared with air-based and single-phase liquid cooling, two-phase cooling is very attractive since it takes advantage of the phase change mechanisms (evaporation and condensation) to absorb and emit heat. Pumped two-phase cooling provides improved heat transport capability and reliability compared with passive two-phase devices such as heat pipes.

Although perfluorocarbon (PFC) has been widely used as coolant in HEP detector systems such as the ATLAS SCT, CO_2 is consider to be better coolant due to much larger latent heat (approximately three times larger). In addition, we can use thinner cooling tubes for CO_2 coolant due to smaller evaporated vapor volume. Because of these advantages, the AMS tracker and the LHCb-VELO has successfully employed two-phase CO_2 cooling systems mainly developed by NIKHEF, and CERN, FNAL and SLAC started R&D of two-phase CO_2 cooling. Development of two-phase CO_2 cooling system is also important for many industrial applications such as refrigeration for bio-cells and foods.

It is reasonable to choose a gas compressor rather than a liquid pump to circulate CO_2 because the former has many advantages theoretically. On the other hand, the gas compressor requires an oil-free operation under a quite high pressure. This requirement is also widely needed for some applications that use a pure-gas circulation system.

The gas pressure is higher than 1 MPa at almost all of the circuit. It is important from the viewpoint of industrial applications to develop a safe high-pressure gas circulation system. The committee praises that this system has taken an inspection of safety regulations for high-pressure facilities in spite of a small cooling capacity.

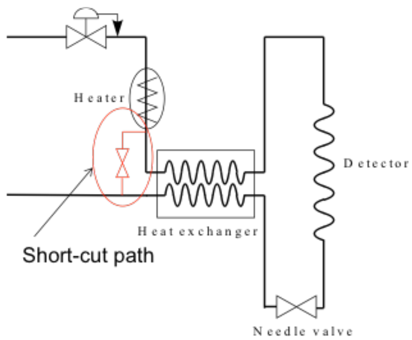
Concerns and Recommendations

Specifications of the cooling system are not shown in the report, in particular, the target size of the cooling system. Large-size system may require different design principles[CO2-1].

It is reasonable to utilize a commercial gas compressor as the first step, however, it is worth considering a possibility to introduce an inter-cooling function to the compressor for the next step. According to the phase diagram of CO_2 circulation, the CO_2 temperature at the outlet of the compressor becomes about 150℃. It is effective that CO_2 is compressed at a lower temperature because its density is high[CO2-2].

In the complicated cooling tube topologies, e.g. many vertical cooling paths, temperature may not be uniform along the cooling tube. It is important to measure temperature and pressure fluctuations at the exit of the cooling tube[CO2-3].

There is only one cryogenic expert in the group. Other members are physicists or electronics engineers. It is better to have more cryogenic experts involving the project even as part-time collaborators. For example, cryogenic experts may suggest adding a short-cut path between the inlet and outlet of the heat exchange as shown the figure to prepare for unexpected accidents[CO2-4].



Response from the group

CO2-1: The expected cooling capacity of the present test system is 800 W at +15°C and 260 W at −40°C. Required capacity for the target system is 2 kW at +15°C and 500 W at −40°C. The cooling capacity of the present system is limited by the capacity of the air compressor for gas booster drive. Factor 2 –3 improvement of the cooling capacity can be achieved by replacing the air compressor with more powerful one.

CO2-2: As the review committee pointed out, utilizing a gas compressor with inter-cooling function is an interesting option. CO_2 gas compressors developed for "ECO Cute" have such function. We will investigate possibility of using such compressors.

CO2-3: It would be interesting to make a large scale dummy load and measure the temperature and pressure non-uniformity. We would like to study it if allowed from the view point of safety.

CO2-4: We had one more cryogenic expert who worked as part-time. But after his retirement, we have only one cryogenic expert. We are eager to involve more cryogenic experts, but KEK cryogenic group is suffering from lack of manpower and we have not succeeded to get more persons. We will do our best to increase the cryogenic experts in our group. We will include the short-cut path suggested by the review committee in the next prototype.