# P2IO Final Report – October 26, 2014

**Title of project**: Development and implementation of semi-conductor sensors to probe the Compton recoil electron spectrum and to measure the beam halo after the interaction point of the ATF2 final focus prototype at KEK (Japan)

**Project responsible and author of this report**: Dr. Philip Bambade (LAL, CNRS/IN2P3 and Univ. Paris Sud)

**Project goals:** The primary technical goal was to develop a beam halo profile monitor suitable for operation in the vacuum chamber of the ATF2 beam line at KEK, capable in particular of withstanding a high radiation environment and of achieving very fast measurements over a very large dynamic range. In this context, we rapidly opted for diamond sensors, because, while they are expensive, they do combine all the wanted features. The directly related scientific goal was the investigation and characterization of the beam halo generation mechanisms and transport, both through calculations and measurements at ATF2. A secondary important technologically oriented goal was also learning about diamond sensors more generally, in order to master both the in-house handling of several fabrication aspects, and the usage for a range of diverse conditions. In relation to the above, we also wanted to consider specific applications of diamond sensors for other projects, especially the fast luminosity monitoring project which we have become involved in for SuperKEKB. Our P2IO activity served as an efficient springboard enabling us to make a suitable technical proposal and to obtain European funding for it within H2020. Finally, we also had some educational goals (as in all our projects), in particular in the context of training students, both at PhD or master level and undergraduates.

## Description of work achieved:

- <u>Testing and characterization of diamond sensors in air</u>. We have bought several single crystal CVD diamond sensors, initially from Diamond Detector Ltd, later from CIVIDEC, and tested them in our clean room with $^{241}$Am $\alpha$ and with $^{90}$Sr $\beta$ sources as well as in the 3 MeV electron beam of the PHIL photo-injector facility at LAL. The tests have demonstrated the ability to detect signals and operate the sensors over an enormously large dynamic range, from single particles and up to beams of $10^8$ electrons. For measurements with single electrons, the signal must be amplified. We used a fast charge amplifier developed by CIVIDEC with a shaping time of 10 ns FWHM, about 1000 electrons of noise, and producing pulses with about 5.4 mV / fC of charge. With this amplifier, the S/R for 1 MIP is about 18 for a 500 $\mu$m thick diamond sensor, enabling the Landau energy loss distribution to be easily reconstructed. We also used a very high bandwidth (2 GHz) current amplifier. In that case, although it has about ten times more noise, which makes it suitable only for the tail of the Landau from electrons, or for the larger energy deposits from $\alpha$ particles, the shape of the individual pulses could be studied in detail. This enabled us to measure the transit time of electrons and holes separately as a function of the bias voltage. It allowed us to calculate the drift velocity of both types of carriers and to reconstruct the lifetimes. Results obtained are not yet published, but agree with other results in the field. Some of these results will be described the PhD thesis of Shan Liu. In parallel, several measurement campaigns were also conducted in the PHIL electron beam. In this case, the signals are huge and typically require attenuation. All the electronics and acquisition is placed in the control room, after about 100 m of Heliax ½ and ¼ inch fast coaxial cable (with negligible signal loss or broadening). These tests could be performed easily in air just after the exit window of the beam line. A remotely controlled translation stage was used, to enable scanning of the sensor across the beam distribution. Calibration and comparisons were also done with other instruments, in particular a LANEX screen positioned on the same translation stage, with sensitivity down to about $10^5$ particles, a YAG screen inside the vacuum chamber and integrating current transformers along the beam line. While absolute calibrations don't fully agree among all these instruments, we could demonstrate a linear behavior of the integrated charge signal from the diamond sensor from $10^5$ to $10^8$ particles. We observed that the signals significantly broaden and develop long tails above about $10^6$ incident particles. The broadening and tails are explained by a drop in the effective bias voltage, which develops as the intense pulses are forming from such large incident charges, due to the instantaneous current in the output resistor and due to space charge effects as the electrons and holes separate in the diamond material. A simplified ab initio model has been developed which shows many of the observed features for large signals from such beam. Above $10^8$ particles, the signals are slowing down enough that some of the carrier transit times extend beyond their expected mean lifetime. This can lead to electron-hole recombination. Some saturation of the collected charge, seen for the highest incident charges, is thought to originate from that.

- Design and initial testing of a diamond strip in-vacuum beam scanner. Based on our learning experience and collaborating with CIVIDEC, we have designed and ordered a set of four diamond strip in-vacuum beam scanners and prepared the mechanics for installation and operation at both PHIL at LAL, and ATF2 at KEK (Japan). The devices are identical and interchangeable, allowing convenient tests and studies in our home environment at LAL before shipping and using at KEK. The diamond sensor is also a single crystal CVD, metallized with two narrow (100 $\mu$m) and two broad (1.5mm) strips on one side. The differing widths are to enhance the dynamic range. In addition, a low pass filter with a few Hz band pass is used on the ceramic PCB, together with large charging capacitors on the HV side. Readout is done first through the metallized lines on the PCB and on to a 50 Ω matched in vacuum coaxial cable. The first two devices have been received in May at LAL and were tested both in the clean room and in the PHIL beam line. Clear signals are seen from all strips and both the scanner and fast digital sampling scopes are operating under MATLAB control for convenient profile measurements. Some inter-strip capacitance has been observed and will be analyzed in detail. Although it is not a requirement, it is expected that some additional spatial resolution can be gained from the resulting signal sharing on neighboring strips. Some electromagnetic beam pick up was also observed, although much weaker than typical signals from beam charges traversing the diamond. This will need investigation to assess the lower part of the dynamic range. The first unit was sent to KEK last week and will be installed in the first week of November. We expect first beam halo measurements at ATF2 with this device in November and December. This work will be the main part of Shan Liu's PhD thesis.

- Simulation of the beam halo propagation from the entrance of the ATF2 beam line to the planned sensor location after the interaction point. A detailed simulation including the aperture profiles along the ATF2 beam line allowed identifying the location of losses due to interception of beam halo, and to evaluate the shape of the propagated distribution in the region where the Compton electron signal will be measured. A GEANT4 study of potential regeneration of vertical beam halo hitting the beam pipe in the last bending magnet (one of the main locations where halo is intercepted) was also pursued. A study of halo collimation upstream in the ATF2 beam line is also on-going, in collaboration with the IFIC-Valencia group. A theoretical and simulation effort to model beam halo generation mechanisms in the ATF damping ring has also been pursued in collaboration with the IHEP group in China, taking into account effects from both intra-beam multiple Coulomb and beam gas Bremsstrahlung and Coulomb scattering.
- Measurements of beam halo at ATF using carbon and W wire scanners. Beam halo measurements were pursued at the ATF2 beam line at KEK using existing instruments (carbon and W wire scanners), in collaboration with the IFIC-Valencia group. Horizontal and vertical measurements were done in the dispersion free diagnostic section and a region fraction of meter after the interaction point where beams are nominally focused (respectively to 10 μm and less than 50 nm horizontally and vertically). The signals from the wires are bremsstrahlung photons collected in a photon detector after a bending magnet (Cherenkov or scintillator device). Several issues were found. On the one hand, a large dynamic range is not possible without combining data sets from several HV settings of the PM tube. Since the gain of a PM is highly non-linear with HV, such combination is not very convenient. In addition, bremsstrahlung photons produced by beam halo intercepted in the nearby environment (e.g. the beam pipe, or even neighboring wires on the scanner fork) are often also detected, resulting in a baseline severely limiting the dynamic range. Nonetheless, beam halo tails up to 4-5 standard deviations of the beam core could be

measured. A parameterization of the non-Gaussian part of the distribution was derived and compared with previous studies in that range. In addition, the shadow of an existing adjustable collimator could be tracked during its movement.

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

Our project aims at developing appropriate tools and methodology to assess and control beam halo in accelerators for particle physics. This has very high relevance for the operation of high energy high luminosity colliders, since beams must be focused down to extremely small transverse dimensions, with the consequence of driving halo particles out towards the beam pipe at locations close to the interaction point. Beam halo collimation is a particularly tricky and critical aspect of all presently operating and future collider, since a trade-off exists between the highest luminosity and acceptable background conditions for the experiments. The knowhow which we develop through this project has thus a high added value in terms of contributing to create acceptable experimental conditions for existing and future colliders for particle physics, which is one of the main research areas of P2IO. In addition, the mastering of the diamond sensor technology is a clear asset to our community. Our instrumentation is based on mono-crystalline chemical vapor deposition diamonds, whose radiation tolerance and fast signal collection enable usage under very high particle fluxes, for beam diagnostics at several intensity frontier machines, ATF2, SuperKEKB and also ILC/CLIC or post LHC machines. It requires fast electronics readout system developments. R & D studies realized in this context contribute to our expertise in both detector and electronics readout technologies at the state of the art. Our work is relevant to prepare our team and laboratory for future projects in which diamond sensors will be needed. The outcome of our project clearly contributes to enhance the visibility of the P2IO LABEX in the HEP community.

## Possible valorization of the project:

A possible valorization has not yet been defined in a concrete way. However, our project at LAL also includes the goal to produce our own sensors based on metallized electronic grade sCVD diamonds purchased from Element Six Ltd (or other producers – there are some, but not as established as Element Six Ltd). We have already acquired four diamonds from Element Six Ltd, two metallized with Ti/Pt/Au and two with Al. Electrical properties have been tested and are satisfactory (I-V curves showing order of 1-2 pA leakage current in the range of bias voltages between + and - 500 Volts). The next step will be to produce the PCB with appropriate HV filter and charging capacitors. The electrical connections to the surface electrodes can be made either by bonding on one side and gluing with conductive glue on the other, or by mechanical clamping. Support from our electronic department is being discussed in the context of assigning an engineering physicist from that group on a part time basis. If in the future we succeed in making reliable sensors ourselves, overall costs will be much reduced compared to purchasing from CIVIDEC. We could then consider providing such sensors to other research groups or laboratories, as a service or for a fee.

## Future of the project after P2IO funding:

It is clear that our work will continue after the end of the P2IO funding. Not only are sensors now available for beam halo studies at both KEK/ATF2 and LAL/PHIL, but we have also started the design of a luminosity monitor for SuperKEKB. The requirements for the latter are quite different (mainly speed, as opposed to understanding the linearity of the response over a large dynamic range at ATF2 and PHIL). Our activity has received substantial European funding through two H2020/MSCA/RISE contracts, which secure our travel budgets for the next four years to work at KEK. In addition, a recently hired associate researcher (Viacheslav Kubytskyi, CDD IN2P3) has as his main topic the modeling and operation of our diamond sensors. Two PhD students, respectively in the 3$^{rd}$ year (Shan Liu) and 2$^{nd}$ year (Dima El Khechen), each also spend significantly more than half their time working with the concepts and instrumentation developed within our P2IO project. Finally, a new master student will join the project in the spring (from Ecole Centrale de Lille), and we expect a new PhD student to take over from Shan Liu when she finishes in about a year.

Another reason for continuing with diamond sensors at LAL is the project to produce our own sensors (based on metallized electronic grade sCVD diamonds purchased from Element Six Ltd) which was launched with the instrumentation group at LAL. This project is still barely started, but has now received the attention of the management. Engineering support is expected in the next few months. Diamond sensors are actually needed in several other projects which LAL is either directly involved in, or has an interest in:

- The ELI-NP group at LAL is planning to use a diamond sensor to monitor their photon beam. They have started computations and will use one of our in-air sensors for initial tests. They need an in-vacuum sensor not very different from the one which we have installed at PHIL and ATF2, but without the complexity of strips. Their timing requirements are also a factor 4 less stringent than for our luminosity monitoring project at SuperKEKB.
- The UA9 bent crystal collimation project at CERN presently uses Cherenkov counters developed by a contributing group at LAL to measure the extracted proton rate and thereby evaluate the efficiency of the beam halo cleaning. Diamond sensors could be an excellent alternative, due to their speed, compactness and radiation hardness.
- The positron source for the SuperKEKB project at KEK needs a diamond sensor to monitor the electron beam on the target. It is also an in vacuum design, in a rather extreme radiation environment. They are consulting with us within the Toshiko Yuasa France Japan Particle Physics Laboratory about the design.

The permanent staff LAL involved in this project are: one electronics engineer (specialist of fast digital systems and feedback), one mechanical engineer, one electronics technician participate, and we hope to involve, as mentioned above, one engineering physicist.

## Publications:

*Diamond sensor study and development*

1. Status of Diamond Detector Development for Beam Halo Investigation at ATF2 , by S. Liu et al.: THPME092.PDF, presented at the 5th International Particle Accelerator Conference (IPAC 2014), Dresden, Germany, 12-17 June 2014
2. Measurement of Low-charged Electron Beam with a scintillator Screen , by T. Vinatier et al.: THPME094.PDF, presented at the 5th International Particle Accelerator Conference (IPAC 2014), Dresden, Germany, 12-17 June 2014
3. Development of Diamond Sensors for Beam Halo and Compton Spectrum Diagnostics After The Interaction Point of ATF2 , by S. Liu et al.: MOPME003.PDF, presented at the 4th International Particle Accelerator Conference (IPAC 2013), Shanghai, China, 12-17 May 2013

*Beam halo and collimation*

1. Design and Feasibility Study of a Transverse Halo Collimation System for ATF2 , by N. Fuster-Martinez et al.: MOPRO033.PDF, presented at the 5th International Particle Accelerator Conference (IPAC 2014), Dresden, Germany, 12-17 June 2014
2. Beam Halo Measurements using Wire Scanners at ATF2 , by S. Liu et al.: THPME091.PDF, presented at the 5th International Particle Accelerator Conference (IPAC 2014), Dresden, Germany, 12-17 June 2014
3. Analytical estimation of ATF beam halo distribution, by D. Wang et al.: arXiv:1311.1267, IHEP-AC-LC-Note2013-020, Accepted for publication in Chinese Physics C
4. BDSIM-GEANT4 modeling of beam halo regeneration from vertical beam losses in BDUMP magnet beam pipe , by I. Khvastunov et al.: ATF-13-02
5. Propagation of a beam halo in accelerator test facility 2 at KEK , by S. Bai et al.: Chinese Physics C 2013 Vol. 37(5): 057005

*Fast luminosity monitoring at SuperKEKB*

1. Fast Luminosity Monitoring using Diamond Sensors for the Super Flavor Factory SuperKEKB , by D. El Khechen et al.: THPME090.PDF, presented at the 5th International Particle Accelerator Conference (IPAC 2014), Dresden, Germany, 12-17 June 2014
2. Fast Luminosity Monitoring using Diamond Sensors for Super Flavour Factories , by C. Rimbault et al.: MOPME004.PDF, presented at the 4th International Particle Accelerator Conference (IPAC 2013), Shanghai, China, 12-17 May 2013

## Expenses:

Total travel budget: **15250 euros**

- 2012: **3404** (2824 for LCWS Arlington – P. Bambade, 582 for ADAMAS diamond workshop – P. Bambade and S. Liu)
- 2013: **4956** (2920 for ATF2 experimentation at KEK – S. Liu, 279 for halo collimation meeting in Valencia – L. Riu, 928 for ECFA LC workshop Hamburg – S. Liu, 768 for meeting and diamond testing with CIVIDEC at CERN – P. Bambade and S. Liu, 61 for meals at Saclay workshop on LC – P. Bambade)
- 2014: **6884** (6117 for ATF2 experimentation and meetings at KEK – P. Bambade and S. Liu, 767 for meeting and diamond testing with CIVIDEC at CERN – P. Bambade and S. Liu)

Total equipment budget: **39750 euros**

- 2012: **11495** (2858 for first diamond sensor, 6427 for 4 sCVD diamonds, 2210 for electronics)
- 2013: **17555** (1124 for electronic components, 2018 for laptop, 1336 for low attenuation coax cables, 900 for high BW current amplifiers, 9647 for 2 Keithley sourcemeters, 1540 for high BW current amplifiers, 990 for mechanical vacuum component)
- 2014: **10683** (1540 for fast charge amplifier, 5633 for fast 1 GHz sampling ADC and FPGA, 1273 for PC, 224 for electronic components, 239 for mechanical vacuum component, 374 for transport box, 1194 for set of high BW attenuators and 50 Ohm terminations, 53 for in vacuum coax cable connection, 153 for LV supply)