# Innovative diamond based detector development for charged particle detection

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In the frame of multi-disciplinary collaborations:
IP2I, DIAMFAB, ESRF, RSRM-UGA, ARRONAX, LSPM, ILL, LPC-Caen, CERN-RD42
AIST, Tsukuba University


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***The scientific context***

## Nuclear Physics

- **Alpha particles, Neutron, short range particle detection**

High energy deposition in few µm
Charge, mass, kinetic energy identification

→ *good energy resolution (~1% RMS)*
→ *good time resolution for time of flight (<100 ps)*

## Particle Physics

- **Beam monitoring (LHC, KEK,J-PARC)**
- **Inner tracking detectors** for future colliders

→ *ultra-high fluences*
→ *long range operation*
→ *high sensitivity : Minimum Ionising Particle (MIP) detection*

## Medical Physics

- **Beam monitoring for radiotherapies** (position/time stamp/charge counting)

→ *very large area (>1cm$^2$)*
→ *high count rate (100 MHz)*
→ *good sensitivity and high dynamic (single proton detection in bunches up to 10$^{10}$ in train of bunches for the very innovative « flash » therapy)*

***The objectives of the project***

**Innovative diamond detectors development from :**

**diamond growth + ion implantation + electronic development (fast preamplifier, QDC, TDC, ASIC and discrete FE readout electronics) + detector assembly + access to radiation facilities**

⇒ **ΔE – E diamond monolithic detector**
⇒ ***PN junction development***

⇒ **Need for high quality, pure, affordable, reliable, large area diamond single-crystal detectors**

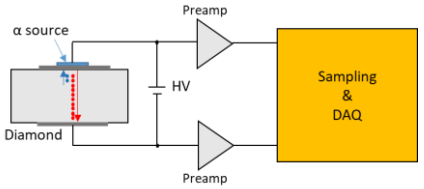
⇒ **Compact multi stripped diamond detector associated to a multi-channel readout electronics (fast preamplifier, QDC, TDC)**

# Diamond a solution for very innovative detectors with remarkable properties

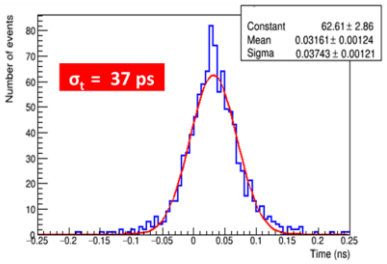
| Properties | Diamond | Silicon |
|---|---|---|
| Density [g.cm$^3$] | 3.52 | 2.33 |
| Gap [eV] | 5.48 | 1.12 |
| Energy required to produce e-h[eV] | 13.1 | 3.62 |
| Mean signal MIP [e-/µm ] | 36 | 89 |
| Resistivity [Ω.cm] | $10^{13} – 10^{16}$ | $10^5 – 10^6$ |
| Thermal conductivity [W.cm$^{-1}$.K$^{-1}$] | >1800 | 1.48 |
| Displacement energy [eV] | 43 | 25 |
| Electron mobility [cm$^2$.V$^{-1}$.s$^{-1}$] | 1900 | 1450 |
| Hole mobility [cm$^2$.V$^{-1}$.s$^{-1}$] | 2300 | 505 |

**Compared to other semiconductor detectors, such as silicon ones, diamond based detectors exhibit several advantages :**

- A high resistivity (>$10^{13}$ Ω m) coupled to a large electronic gap (5.48 eV) results in a lower noise level and an almost negligible leakage current even at room temperature (few nA).
- Despite the fact that the energy required to produce electron-hole pairs is 3.6 times larger than in silicon, the signal to noise ratio is higher for diamond.
- The high charge carrier mobility leads to a very fast detector response allowing excellent time resolution

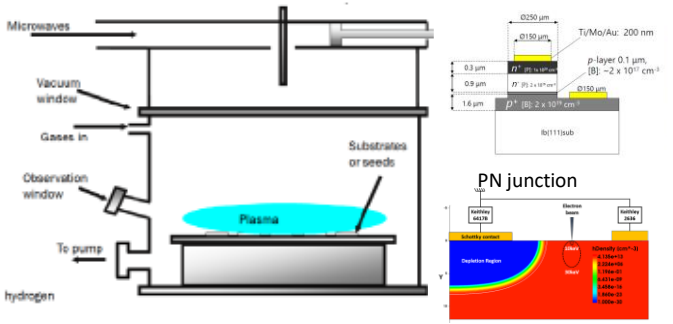



**Time resolution (offline Constant Fraction Discrimination)**



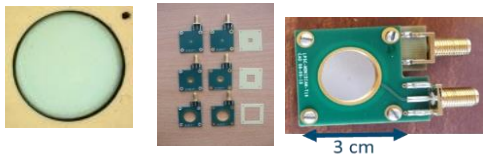

# R&D with diamond detectors and complementarity of the consortium

## CVD Diamond growth, doping, characterization




NIMS - Institut Néel

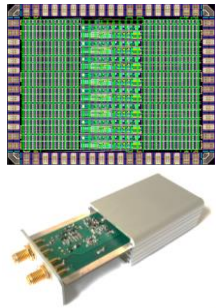
## Metallized diamond detector assembly



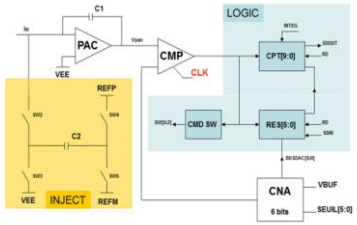

KEK – LPSC – NANOFAB Néel

## Diamond detector electronic read-out development

**Fast preamp.**



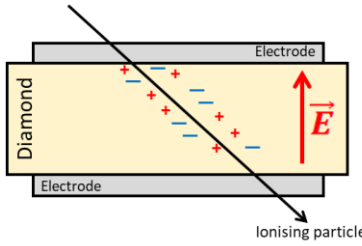
**QDC**




*Gallin-Martel, IEEE NSS-MIC 2016*

KEK - LPSC

## Diamond detector performances evaluation with radiation facilities

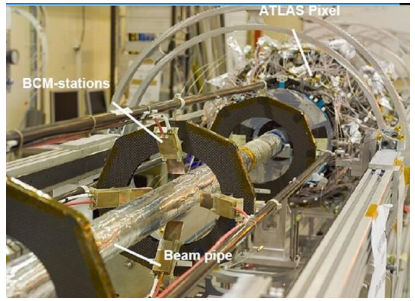



KEK - LPSC – IJCLab- SUBATECH

*Present experience with on-line beam monitors*

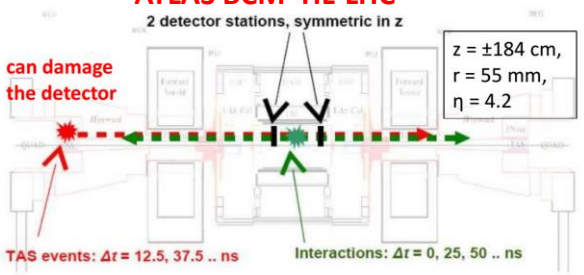
## LHC ATLAS and CMS

ATLAS BCM



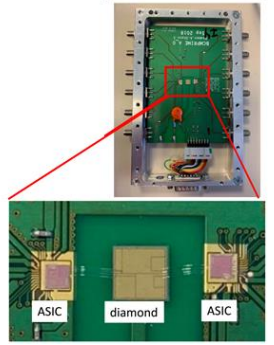

**RD42 collaboration @ CERN** https://rd42.web.cern.ch/rd42/

ATLAS BCM' HL-LHC




Robust solution for HL-LHC→ BCM' (BCM Prime)

ATLAS BCM' HL-LHC

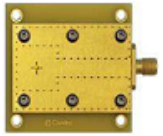



**F. Rarbi,** J Collot (LPSC)

## SUPERKEK B

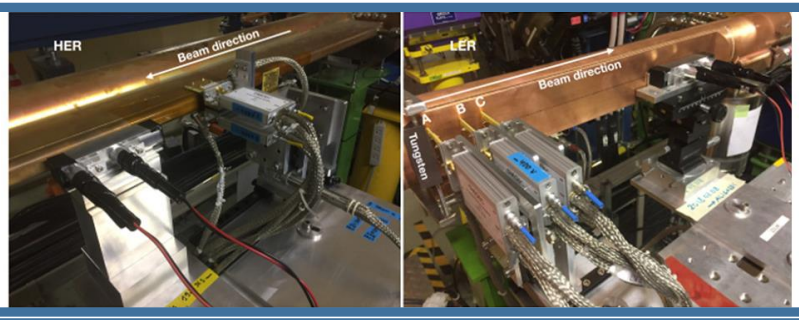
A fast luminosity monitor based on diamond detectors for the SuperKEKB collider

Diamond detector



**Ph. Bambade** (IJCLab), C. G. Pang et al.: Nucl. Instrum. Meth. A931 (2019) 225-235

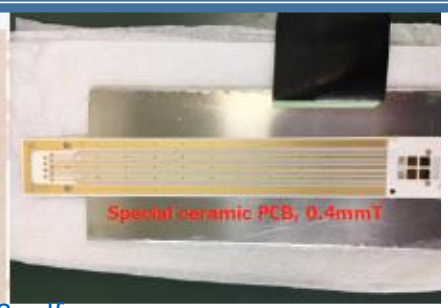
https://doi.org/10.1016/j.nima.2019.03.071

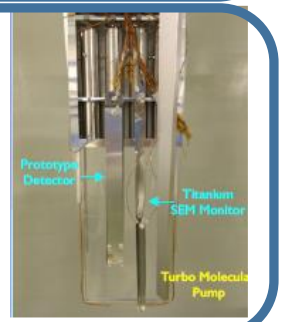



## COMET experiment

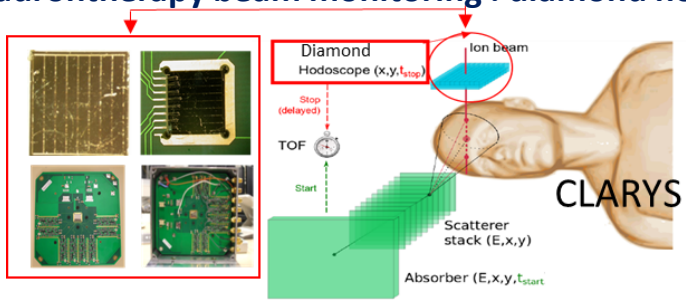
Search for the muon to electron (μ- e) conversion in nuclei with the sensitivity below $10^{-16}$ => development of a diamond based proton beam monitor

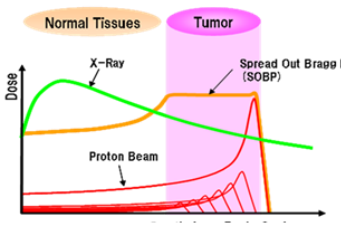
Y. Fujii, **H Nishiguchi**, S. Mihara, Y Hashimoto (KEK Tsukuba)
14th Pisa meeting On Advanced Detectors
Labiodola, Isola d'Elba, Italy, 2018
https://agenda.infn.it/event/17834/contributions/83592/attachments/60425/71543/276-Poster-fujii-yuki_Pisameet18.pdf

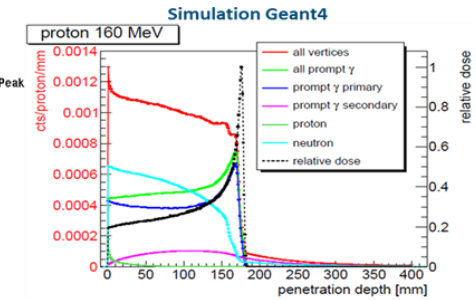




## Hadrontherapy beam monitoring : diamond hodoscope coupled to a Compton camera for prompt gamma detection

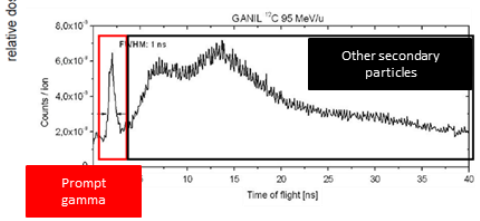



Krimmer et al., Nucl. Instr. Meth. A, **878** (2017) 58-73

Prompt gamma selection with Time of Flight

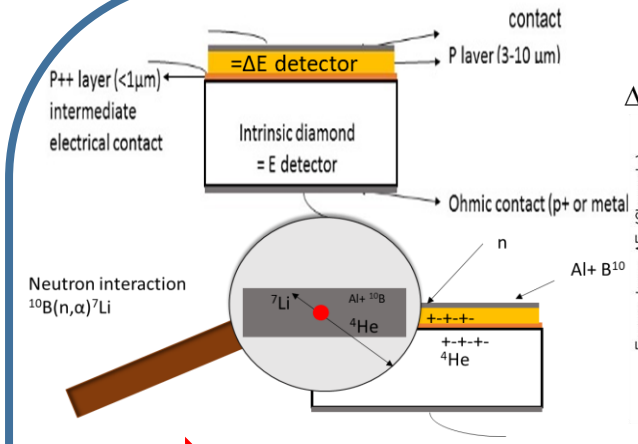



Mauro Testa, Thèse, Univ. Lyon, 2010

**ML Gallin-Martel et al.** (LPSC) https://doi.org/10.1051/epjconf/201817009005

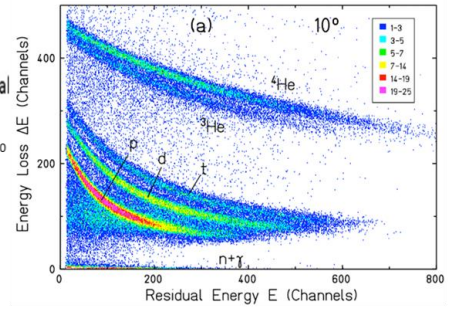
# *Foreseen development : design of a monolithic diamond ΔE-E telescope and PN junction for short range particle detection*

## PHD student Alexandre Portier




$^{12}$C 200 MeV/u ions Gunzert-Marx 2008

$\Delta E \sim Q^2/v^2$



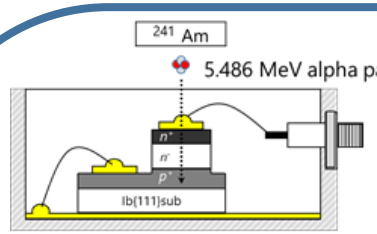

$E \sim A$

➡ Neutron detection + short range particle detection

DiamFab Institut Néel ➔ CVD process of a high quality epitaxial diamond layer with a good-controlled boron doping concentration

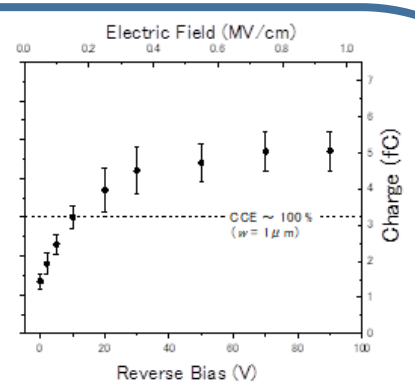
- This detector relies on commercial diamond substrates.
- On the top side, a few µm-thick metal contact with a stack of highly doped layer (allowing metallic conduction)
- Lightly undoped layer will be designed to collect charges induced by the incident particle with a good time resolution.
- On the back side, a second metallic contact will be deposited.

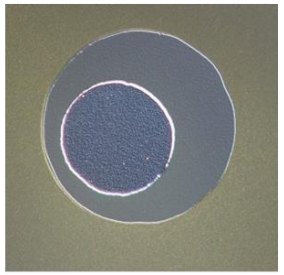
Approuved in the project « R&T DIAMTECH » by IN2P3 on years 2020-2022



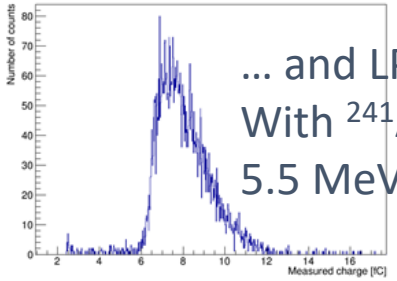

Charge collection efficiency (CCE)

$$CCE = \frac{Q_{collected}}{Q_{induced}} \times 100\ (\%)$$



Alpha particle detection done at KEK ….




… and LPSC With $^{241}$Am 5.5 MeV

PN Junction from NIMS

NINS, KEK ➔ pn (PIN) junction device formation by n- and p-type doping with high quality device processing combined with KEK radiation sensing technologies.

- High quality pin structure will be formed to detect alpha and beta particles with intrinsic electric field.
- Structural optimization will be performed to get better signal response of the devices.

# *Conclusion*

The associated partners have already demonstrated in the past the skills to perform the foreseen developments and characterizations:

- the activity has been supported in **2019-2020 by the PRCE JSPS-CNRS program** : an international conference was set-up in Yuzawa (2019) https://www.nims.go.jp/Diamond_detector_workshop/ (to download abstract : “diamond-detector”)
- The **LPSC** has an expertise in detector development for particle physics (ATLAS) and medical physics (beam hodoscope for hadrontherapy).
- The **KEK** group is experimented by problematics linked to particle physics and beam accelerators. **KEK-NIMS** has developed a new diamond-base beam monitor for J-PARC proton accelerator
- **SUBATECH and GIP-ARRONAX** are skilled with the problematic of physics with accelerators.
- The **IJCLab** is already involved in the lumiBELLE2 project and is used to the use of diamond for fast luminosity measurement at KEK.
- **NIMS** has an expertise in diamond growth and doping.
- **Néel** has an international recognition in development of diamond high power electronic devices, diamond processing and eBIC.

The aim of the present proposal is to allow useful exchanges and transfers of knowledge between the associated groups with respect to the production, characterization and use of diamond sensors for the new demanding applications in terms of charged particle detection and beam monitoring currently under consideration in Japan and in France.

**A. Portier, a French PHD student (LPSC - Néel) is involved in the project and the project fundings will permit him to participate to the chips tests in Japan**.