Application of Diamond Detectors in Tracking of Heavy Ion Slowed Down Radioactive Beams

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Low energy RIBs at the GSI-NUSTAR facility

γ-spectroscopy experiments at Coulomb barrier energies
- multiple Coulex
- direct reactions and DIC
- fusion-evaporation reactions

RIB of all elements
- $\tau > 100\text{ns}$
- 5-100 AMeV
- $10^7$ ions/s

The Energy Buncher shifts phase space from longitudinal ($\Delta p/p$) to transversal phase space (size/angle)
- Momentum definition $\Delta p/p < 5$
- Large beam spot $\sim 10\times10\text{ cm}^2$

SIS 100/300 ($p-U$)
- 400-2700 AMeV
- $10^{12}$ ions/s
HIgh resolution in flight SPECtroscopy

Low energy RIB experiments will imply:
- a projectile velocity and position spread
- Doppler broadening of $\gamma$-lines
- high $\gamma$-ray multiplicity
- enhanced particle and $\gamma$-ray background
- high count rate

AGATA

γ-ray tracking

Reaction product identification

γ-ray tracking AND projectile tracking:
- identification
- position
- velocity vector

good resolution high sensitivity
Tracking detector characteristics

What a particle detector can fulfil the following requirements:

- timing better than 100 ps
- energy resolution of about ~1%
- efficiency close to 100%
- minimum thickness
- radiation hardness (HI rates of $10^7$ ions/s)
- position resolution better than 1 mm$^2$
- large covering area (10x10 cm$^2$)
### Superior properties of diamond as a charged particle detector

<table>
<thead>
<tr>
<th>Property</th>
<th>Silicon Z=14</th>
<th>Diamond Z=6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Band gap [eV]</td>
<td>1.12</td>
<td>5.5</td>
</tr>
<tr>
<td>Dielectric constant</td>
<td>11.9</td>
<td>5.7</td>
</tr>
<tr>
<td>Resistivity [Ωcm]</td>
<td>$2.5 \times 10^5$</td>
<td>$10^{11}$</td>
</tr>
<tr>
<td>Thermal conductivity [W/cmK]</td>
<td>1.5</td>
<td>20</td>
</tr>
<tr>
<td>Carriers mobility [cm²/Vs]</td>
<td>e: 1350</td>
<td>4500</td>
</tr>
<tr>
<td></td>
<td>h: 480</td>
<td>3800</td>
</tr>
<tr>
<td>Displacement energy [eV]</td>
<td>24</td>
<td>80</td>
</tr>
<tr>
<td>e-h pair creation energy [eV]</td>
<td>3.6</td>
<td>13</td>
</tr>
</tbody>
</table>

- **Operation at RT**
- **Small capacitance, noise reduction**
- **Negligible leakage current, noise reduction**
- **The best known heat conductor**
- **Fast signals**
- **Radiation hardness**
- **Small induced signal**

**Applications:**
- Beam monitoring: CERN, GSI
- ToF spectrometry, GSI, MSU

**Position sensitivity:**
- Stripes
- Pixels

**Ionizing particle HV 1V/μm**

**Applications:**
- Beam monitoring: CERN, GSI
- ToF spectrometry, GSI, MSU
Chemical Vapour Deposition - a breakthrough in diamond detectors production

Natural, HPHT synthetic diamonds
- High costs
- Limited sizes
- Impurities

Poly crystalline - CVDD:
- $\varnothing = \text{up to } 5''$, 1-500 $\mu$m
- $CCE \approx 50\%$
- detection efficiency $\sim 70\%$
- fast timing
- price 2.5 US$/mm^2

Single crystal - CVDD:
- 4 x 4 mm$^2$, 1-500 $\mu$m
- $CCE = 100\%$ - good energy resolution
- detection efficiency $\sim 100\%$
- fast timing
- price 50 US$/mm^2

Element Six (UK):
1 x 1 cm$^2$ SC CVDD

HISPEC/DESPEC meeting 18-19 Oct. 2006
Till now diamond detectors were used with:

- MIP - SC CVDD energy resolution comparable with Si
- HI at AGeV energies - ToF time resolution <100 ps

**Purpose of the work:**

In-beam evaluation of time and energy measurements with diamond detectors at a low beam energy and a high particle rate

CNA-Seville 3MV tandem laboratory
The CNA-Seville 3MV tandem

- 5.8 MeV p
- 8.7 MeV α
- 11.2 MeV $^7$Li
- Rutherford scattered projectiles
- Defocused beams
  $10^7 - 10^9$ ion/s$^2$cm$^2$
### The CNA experiment participants

<table>
<thead>
<tr>
<th>Institution</th>
<th>Participants</th>
</tr>
</thead>
<tbody>
<tr>
<td>GSI, Darmstadt, De</td>
<td>E.Berdermann, J.Gerl, M.Górska, I.Kojouharov, M.Pomorski, M.Rędisz, B.Voss</td>
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<tr>
<td>University of Seville, Seville, Es</td>
<td>M.Alvarez, J.M. Espino, J.L.Flores, I.Mukha</td>
</tr>
<tr>
<td>JINR, Dubna, Ru</td>
<td>R.Wolski</td>
</tr>
</tbody>
</table>
Detectors

- SC CVDD detectors: 4x4mm², 110-500 μm (GSI Detector Laboratory)

- PC CVDD 4-fold segmented detectors: 1x1cm², 13-60μm (GSI Plasma Physics dept)
Energy resolution of a diamond detector

“RBS” setup for a low rate measurement:
- Broadening due to a target thickness
- $\Delta E < 50$ keV (1%)
Time correlation

- 110μm SC CVDD vs 300μm SC CVDD, 6MeV p
- 13μm PC CVDD vs 300mm SC CVDD, 11.2 MeV ⁷Li

Traversing 6MeV p:
ΔE=3MeV

3ns

3MeV p

110μm SC CVDD

broad band voltage preamp.

300μm SC CVDD

Typical for a stopped particle trapezoidal shape - 100% CCE

Fast signal rise time, limited by the electronics used
Why the thin detector energy spectrum has two components?

- Edge effect
- Distance from a contact
Test with a high beam current

- Low noise level
- No DC offset
- No leakage current
- No signal degradation with a measurement time
- No dead time
- Worsening of the energy and the time resolution - can be due to unfavourable beam properties

Direct irradiation with a defocused beam (estimated beam flux: $10^7$-$10^9$ particle/s cm$^2$)
Conclusion

- PC CVDD and SC CVDD detectors are suitable for low energy ion detection at a high count rate
- SC CVDD detector energy resolution is of the order of 1% (similar to Si)
- The both detector types exhibit excellent timing properties resulting in ToF resolution below 100ps

- Thinner SC CVDD detector are awaited
- New electronics expected for a fast signal treatment

- Further tests with heavier ions are planned
- Investigation of the CCE (energy resolution) in thin SCCVDD detectors is needed
In order to develop reliable and useful diamond hadron detectors, the following technological steps have to be performed:

- feasibility study of an enlargement of the detector area (only 5x5 mm at present);
- study and optimisation of the growth process parameters with respect to crystal lattice perfection, defect density, concentration of residual impurities and to electrical transport properties, such as the charge collection distance, the mobility and the charge carrier lifetime;
- optimisation of the contact properties, using various metals and surface treatments such as plasma treatment and annealing;
- optimisation of the thickness of the epitaxial mono-crystalline layers;
- development of suitable fast, low-noise front-end electronics for spectroscopy and for timing purposes as well;
- systematic studies of the pulse-shape parameter distributions from SC_CVDD detectors;
- test of the radiation hardness of SC_CVDD by irradiation with neutrons and all kind of charged particles (electrons, protons, pions and heavy ions) and photons.
Where are we heading...

- Evaluating different business models on commercialization of diamond detectors and sensors to provide a reliable route to market.
- Focus on surface preparation, thin plates and larger areas.
- Identifying standard detector products (substrates, die & packaging)
- Review material/production costs and delivery with increased demands and potential large area applications.
- Customers asking for custom metallization and packaging, looking at how we can best serve these requests.
- Focus on market opportunities within the HEP and Industrial applications.

*To be the world wide supplier of choice for diamond based detectors and sensors*
Diamond detectors at MSU

Test of diamond detectors at the NSCL

primary beams: $^{16}\text{O} - ^{124}\text{Xe}$
energy: 50 - 150 MeV/u
intensity: 1 - 10$^{12}$ particles/sec

2 single-crystal diamond detectors
(20 $\mu$m + 35 $\mu$m)
in transmission mount

no degradation of time resolution up to rates of
2 • 10$^6$ particles/sec
= 10$^7$ particles/(sec mm$^2$)

intrinsic detector resolution
$\sigma = 15$ ps

$^{78}\text{Kr}, 87$ MeV/u

time resolution
$\sigma = 20.5$ ps

Comparison diamond vs. plastic scintillator
Diamond detectors at MSU
Diamonds for R3B @ GSI

Time Resolution 50 μm Detector

AI beam, 1.9 AGeV
$\tau$ (100 μm) – $\tau$ (50 μm)

Resolution quite independent from reference detector
Resolution limited by noise? Walk correction needed?

Signal amplitude not written to file

Test of Radiation Hardness with H1

IAF diamond 100 μm

Beam: 120 MeV $^1$O
(Munich Tandem)

Beam attenuators 33 and 1000 measurement @ 17kHz and 1 kHz every 30 min

20% signal loss after $10^{13}$ ions/cm² ($^1$O, 120MeV)
Bragg peak, partially stopping...
A diamond detector at extreme conditions

Beam Conditions

- Bunches of lead ions
- 67 elementary charges per ion
- Lateral dimensions: ~1000 \( \mu \text{m} \) ± 400 \( \mu \text{m} \)
- Bunch length ~ 1 \( \mu \text{s} \)
- Kinetic energy 400 Mev / amu (~ 83 GeV)
- Up to 5 \( \times 10^9 \) lead ions per bunch
  \( \approx 4 \times 10^{20} \) eV / bunch \( \times 660 \text{ J} \) (660 MW)

Fools calculation: If the beam is stopped in the diamond it's heated up by ~ 45,000 \( ^\circ\text{C} \).

The aluminum metalization was damaged but still operational after several bunches of the highest intensity. Bonds were molten when they got into the beam.