Diamond Detectors for Heavy Ion Measurements at GSI Darmstadt

E. Berdermann, E. Badura, C. Neyer, R. Schulze and H. Stelzer

1. OBJECTIVES

The purpose of our investigations is the research and development of CVD-diamond films as a new radiation hard and ultra-fast detector material for heavy ion measurements within the energy range of 50 MeV/amu to 2 GeV/amu. At the same time, suitably fast electronics with low noise, high rate capability, and a wide dynamic range were designed and are already under test.

This programme was started in December '95 and aimes at providing diamond counters, single-channel as well as microstrip and pixel detectors. These are intended to be used mainly in two applications

a) as beam intensity counters and beam profile monitors in accelerators
b) in heavy ion experiments as radiation hard start detectors and for the tracking of charged particles.

2. MOTIVATION

2.1. High Rates

In '98 the high current injector of the synchrotron accelerator SIS at GSI-Darmstadt will deliver ion beams with increased intensities up to the incoherent space charge limit of the SIS (Fig. 1). Even for the highest Z available, intensities up to 10^{11} particles/spill are expected. The spill duration is adjustable between 1 and 10 seconds. Absolute particle fluxes have to be known with an accuracy of about 1% in order to determine the cross sections of measured nuclear reactions as well as to optimize the efficiency of particle extraction and beam transportation.

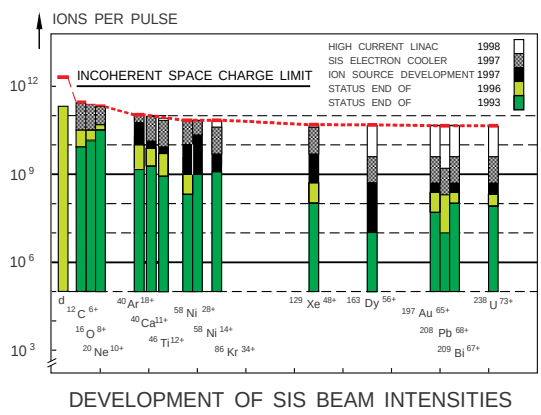

Figure 1. *SIS beam intensities*

To cope with the very high rates we will investigate the suitability of diamond detectors in conjunction with new high-speed electronics, especially designed for this purpose.

2.2. Radiation Hardness

The specific energy loss and the expected mean charge which is generated in silicon and diamond detectors with a thickness of 150 µm are listed in Table 1. The values illustrate the huge energy deposition of heavy ions in solide state detectors and the high dynamic range over the various ion species. The diamond density is taken into account with ρ_{Di} = 3.5 g/cm³, the silicon density with ρ_{Si} = 2.33 g/cm³. The energy required to produce an e^-h pair in silicon is 3.6 eV whereas in diamond the energy amounts to 13 eV.

The unique properties of diamond [1] make us believe that diamond detectors could be most useful in fixed target heavy ion measurements. Up to now, the radiation hardness of diamond detectors has been tested with electrons, neutrons, pions, protons [2][3] and α-particles [4]. All studies done so far indicate a radiation hardness which is by several orders of magnitude higher than the hardness of silicon or GaAs. We plan to extend these measurements in the near future with heavy ion irradiations.

Table 1
Specific energy loss ΔE /Δx and charge amplitude, created from various ions with various velocities in silicon (Si) and diamond detectors (Di) with a thickness of 150 μm.

Ion	Energy [MeV/u]	ΔE/Δx (Si) [MeV/mg/cm²]	charge (Si) [e·hp]x10⁻⁶	ΔE/Δx(Di) MeV/mg/cm²]	charge (Di) [e·hp]x10⁻⁶
^{12}C	50	3.54E-01	3.44	3.99E-01	1.61
	500	8.06E-02	0.78	8.58E-02	0.35
	1000	6.53E-02	0.63	6.85E-02	0.28
^{20}Ne	50	9.90E-01	9.63	1.11E+00	4.48
	500	2.27E-01	2.21	2.48E-01	1.00
	1000	1.84E-01	1.79	1.99E-01	0.80
^{197}Au	50	4.86E+01	472.5	5.44E+01	219.7
	500	1.44E+01	140.0	1.57E+01	63.4
	1000	1.19E+01	115.7	1.28E+01	51.7
^{238}U	50	6.22E+01	604.7	6.96E+01	281.1
	500	2.08E+01	202.2	2.25E+01	90.9
	1000	1.66E+01	161.4	1.79E+01	72.3

2.3. High Charge Response

For the detection of reaction products in heavy ion experiments, where the direct beam does not impinge on the detectors, the radiation and count rate problem is much less severe. The flux of the scattered ions and the reaction products is reduced by a factor of 1000. On the other hand, much better spatial and pulse height resolution are needed than for beam-profile monitors, both for particle tracking and particle identification.

The large dynamic range and the high multiplicity of events with $Z_1 \in [1,Z_{proj}]$ and $Z_2 = 1$ are the relevant factors here. The detectors have to provide fast collection of charge, they must be homogeous and as thin as possible. In the case of micro-strip or pixel detectors they also have to remove heat from the readout electronics. The position resolution required is in the order of 50 μm to 100 μm.

Conventional wire chambers are in-homogeneous due to the wires, they have a thick entrance window and furthermore, they are unable to handle very high rates or to achieve such a good position resolution. Silicon detectors are strongly affected by radiation damage and furthermore, their high charge response leads to saturation effects either in the counters or in the preamplifiers. It is difficult to get resonable large detectors with thickness smaller than 150 μm.

3. TESTS and RESULTS

3.1. Pulse Height Measurements

In the first run in December '95, a 420 μm thick diamond detector was irradiated with ^{20}Ne ions of 300 MeV/amu and with ^{40}Ca ions of 500 MeV/amu kinetic energy, respectively. Negligible leakage current over a wide bias range and a symmetric shape of the IU-characteristic indicate a good quality of the diamond material and an ohmic contact of the metallisation.

Fig. 3 shows the pulse height distributions for both projectiles. The energy loss in the diamond is 118.9 MeV for the Calcium and 46.6 MeV for the Neon ions. The ratio of the pulse height with $^{40}Ca/^{20}Ne$ equals 3.4 was found to be higher than the ratio expected from the Bethe Bloch formula which amounts to 2.6. This observation can

be interpreted as an indication that the charge collection efficiency in diamond detectors improved with the energy deposition in the counter.

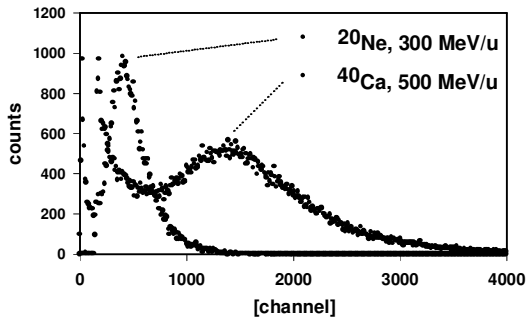

Figure 3. *Pulse height distributions ^{20}Ne 300 MeV/u, ^{40}Ca 500 MeV/u*

The mean charge measured was in the case of the ^{20}Ne ions 1.2 x 10^6 [e-hp] and in the case of the ^{40}Ca ions 4.1 x 10^6 [e-hp]. Both values are considerable higher compared to charge amplitudes measured so far with minimum ionizing particles. Using formula (1) the collection distances can determined to be $d_{cd} \approx 140$ µm and $d_{cd} \approx 190$ µm for Neon and Calcium, respectively.

$$d_{cd} = (cc / ce) \cdot d_D \qquad (1)$$

with cc = charge collected
ce = charge expected
d_D = detector thickness

The reason for this unexpected good result could be a fast filling of the diamond traps due to the high ionization density produced by the heavy ions in the detector material. After this "heavy ion pumping" the charge generated along the particle track will be collected with high efficiency.

In a second experiment in March '96 the same diamond sample was irradiated again with ^{20}Ne ions of 300 MeV/amu. A silicon pin-diode was placed behind the diamond counter and both were aligned perpendicular to the beam axis. Fig.4 shows the fragmentation of the ^{20}Ne projectiles in an iron target.

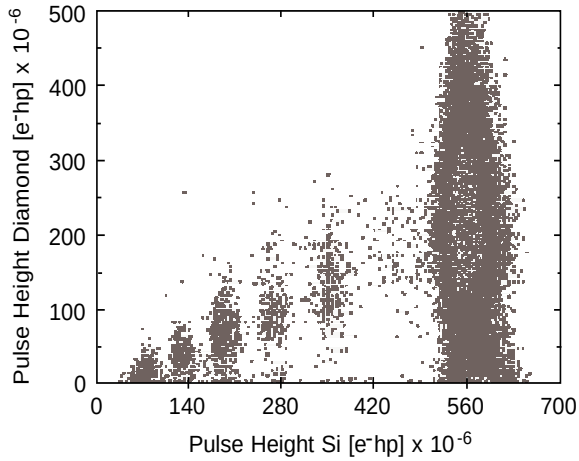

Figure 4. *Fragmentation of ^{20}Ne ions*

The pulse height measured with the pin-diode is plotted versus that of the diamond detector. All fragments from Z=9 to Z=4 are visible. Lighter particles such as alphas and protons are below the threshold.

The most important result from this second run was that the mean values of the collected charge in the diamond counter rises proportionally to Z^2 (Fig. 5). This indicates a very good charge collection of the CVD-diamond counters for selected events which

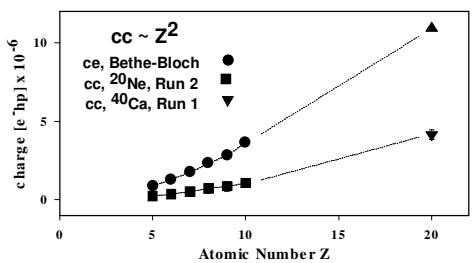

Figure 5. *Z-dependence of the charge response*

occure away from grain boundaries or crystal impurities.

The projectile fragmentation process, measured with a diamond-silicon detector setup, allows an online calibration of the diamond pulse height in MeV $^{(Sili)}$ and

therefore in charge.

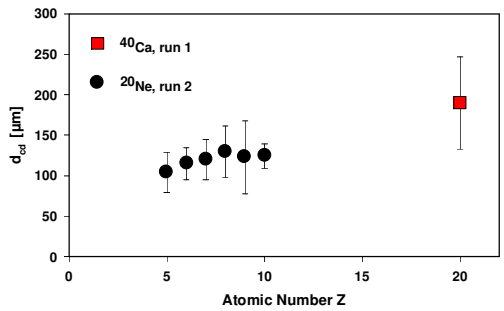

Figure 6. *Z-dependence of the collection distance*

In Figure 6 the data of run 1 and run 2 are plotted as the collection distances d_{cd} versus the atomic number Z of the particles impinging on the diamond detector. Note that the velocities of the Neon projectiles and of the Neon-fragments (Z=10 to Z=5) from run 2 were nearly the same whereas the velocity of the Calcium ions from run 1 (Z=20) was slightly higher. An increase in the collection distance from d_{cd}=100 µm for Z=5 to d_{cd}=190 µm for Z=20 is visible.

In July '96 diamond detectors of various thicknesses were read out in coincidence with a pin-diode and a plastic scintillator. The goal was to measure the dependence of the pulse height resolution on the diamond thickness.

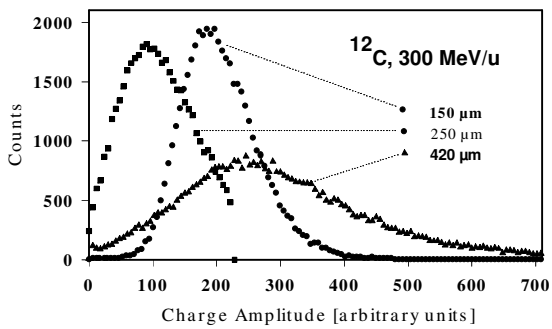

Figure 7. *^{12}C pulse height distributions, measured with diamonds of various thickness*

Figure 7 shows pulse height spectra of ^{12}C ions measured with detectors of 150 µm, 250µm and 420 µm thickness respectively. Assuming a similar quality of the material there is an indication that the resolution improves with smaller detector thickness.

3.2. Time Resolution

Slow and well known electronics were used in all measurements performed in the two first runs. A more suitable one was adapted for run 3 in July '96. A low-noise, charge sensitive preamplifier with 1 GHz band width (Ortec 9306) and an extrapolating double threshold discriminator [5] were used. The discriminator was developed at GSI for operating with very fast streamer/spark chambers such as Pestov-counters.

The measured time resolution between the diamond and a plastic scintillator amounted to $\sigma \approx 400$ ps. By increasing the beam intensity, the σ-width remains small, but the tails of the distribution become broader. Further improvement of the signal to noise ratio is needed for proper timing at low pulse heights.

4. CONCLUSIONS

4.1. Beam Diagnostics

Assuming a useful SIS extraction cyclus of 10^4 spills/day one can deduce from Fig.1 and Table 1 that an Uranium beam with an intensity of 10^{10} particles/spill deposits a dosage of approx. 27 GRad per day in a detector with a thickness of 150 µm. It is expectable that no detector will withstands such high radiation exposures. We have to perform the beam diagnostic measurements such that the lifetime of the counters becomes reasonable. To minimize the damage, the counters will be placed away from the beam waiste. Larger diamond detectors, devided in matching strips or pixels, reduce simultaneously the radiation exposure per unit area and the count rate per readout channel.

4.2. Heavy Ion Experiments

We performed heavy ion measurements with 3 diamond detectors of different thicknesses. Our results confirm so far the expectation that CVD-diamond are a suitable detector material for intermediate and high energy heavy ion experiments . The high ionization density produced by heavy ions leads to a simultaneous "pumping" of the counters, a filling of the diamond traps along the tracks of the particles. The remaining huge amount of charge can then be collected undisturbed. The high break-down field and the high charge carrier mobility avoid space charge problems, well known from other detectors at high rates.

However, to take advantage of the high charge amplitudes produced by heavy ions on one hand and of the speed of diamond detectors on the other hand, further development of low-noise high-speed electronics with a wide dynamic range will be required.

5. FUTURE INTENTIONS

We plan to continue our investigations by testing the behaviour of diamond material during irradiations with various heavy ions. The next experiment will be performed in November '96 with the heaviest ions available at GSI, Uranium ions with a kinetic energy of 1 GeV/amu.

The detector thickness will be reduced step by step. In particular, the pulse height resolution, the signal to noise ratio of the charge response, the time resolution and the rate capability have to be tested for various thicknesses.

Micro-strip and pixel diamond detectors should be developed including readout and metallisation techniques.

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