Diamond Detectors with Subnanosecond Time Resolution for Heavy Ion Spill Diagnostics

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ABSTRACT

Abstract. The application of CVD diamonds as radiation-hard particle detectors with outstanding properties for heavy ion beamline diagnostics is presented. Synchrotron particle spills ranging from a single ion to well beyond 10^8 pps can be analyzed while maintaining single-particle time resolution below fractions of a nanosecond. With segmented electrode structures on the diamond surface, higher particle count rates and improved monitoring of x/y beam profiles can be achieved. Diamond detectors with areas up to 30×30 mm^2 for a precise measurement system for beam intensity, beam profiles, and spill time-structure are described.

INTRODUCTION

The GSI accelerators provide all kinds of ion species in a broad energy range up to 2000 MeV/u. In the high energy beam transport lines, the ion beams extracted from the SIS synchrotron have to be carefully monitored at very different intensities, from a few thousands up to 10^{11} ions per machine cycle. The beam extraction time varies between 10 ms and 10 s. Diamond beam detectors are under development as a unique monitor system especially for the following applications:

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[*] GSI is a member of the RD42 collaboration at CERN. The development of CVD diamond detectors for use in high-energy physics experiments, accelerator facilities, and investigations concerning material characterization and quality improvement are the main aims of the collaboration

- Precise beam intensity measurement using particle-counting techniques ranging from single ions to more than 10^9 ions/s.
- Beam profile measurements by a suitable segmentation of the active detector area, with the ability for dynamic profile measurement during the spill.
- Analysis of the particle spill time-structure using the high time resolution of the new detectors, which is better than 1 ns for low and high beam intensities.

Ensemble of Particle Detectors and Synchrotron Beam Diagnostic Devices

An overview of the counting capabilities of established particle detectors, the cryogenic current comparator (CCC), and the diamond detector is given in Figure 1. The operation ranges of devices used for the observation and measurement of particle beams inside the synchrotrons SIS and ESR at GSI are also shown. One can see that the diamond detectors fit very well into the ensemble. A diamond detector, together with a CCC, can give complete intensity measurement capabilities for all particle beams in the SIS extraction lines. In the lower intensity range, the counting properties of diamond detectors can be verified using scintillators. In the medium range, they can be compared against beam current transformers (BCT) or calibrated ionisation chambers (IC) as well as secondary electron emission monitors (SEEM). In the highest intensity range, calibration can be achieved with the CCC.

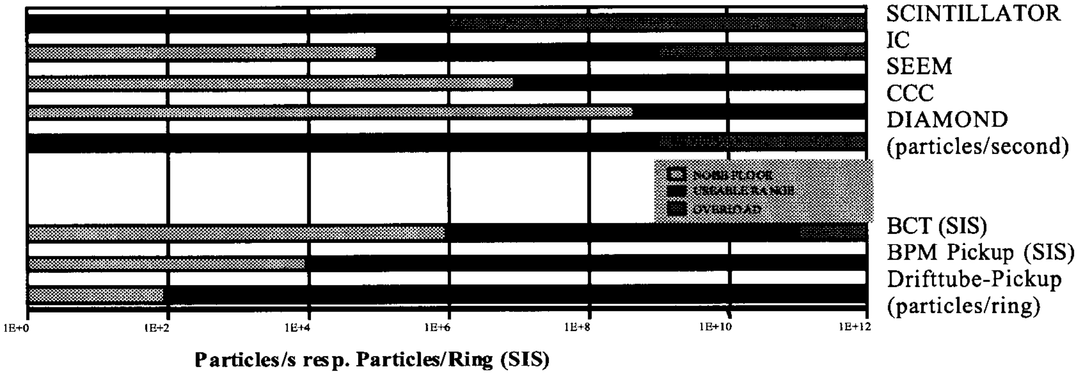

FIGURE 1. Intensity ranges of particle detectors for spill-measurements and of diagnostic devices in the SIS for measurements of the circulating beam

CVD Diamond Properties

Chemical vapor deposition (CVD) polycrystalline diamonds show very promising properties for use in electronics as well as particle detectors. The most important parameters are listed below, together with, for contrast, the corresponding values for silicon.

TABLE 1. Physical Properties of Diamond and Silicon

Physical Property at 300 K	Diamond	Silicon
Band gap [eV]	5.45	1.12
Electron mobility [cm^2/Vs]	2200	1500
Hole mobility [cm^2/Vs]	1600	600
Breakdown field [V/m]	10^7	3×10^5
Resistivity ρ [Ω cm]	$>10^{13}$	2.3×10^5
Dielectric constant ε_r	5.7	11.9
Thermal conductivity [W/cm K]	20	1.27
Lattice constant [Å]	3.57	5.43
Energy to remove an atom from the lattice [eV]	80	28
Energy to create an e-h pair [eV]	13	3.6

The highest thermal conductivity of all known materials (1), and the high energy of 80 eV needed to remove a carbon ion from the lattice lead to the diamond's excellent radiation hardness (2). Due to the large band gap, no p-n junction is required as in the case of silicon counters. After applying metallic electrodes, the diamond sample is ready for use as a detector. The high resistivity of the material allows the application of electric fields up to 6 V/µm. The low capacitance of diamond detectors in conjunction with high carrier mobility are is a basic characteristics for achieving narrow pulses.

Electronics for Diamond Detectors

A heavy ion passing a diamond detector produces a number of e-h pairs along its track, proportional to the energy loss in the material. The produced electrons and holes are separated by an applied electric field and move to the electrodes as long as they are not captured by chemical impurities or grain boundaries in the diamond bulk. This movement of the carriers within the detector's capacitance can be observed as a time-variant signal. The expected number of e-h pairs created by different ion species can be calculated according to the Bethe-Bloch formula. The estimate for the peak amplitude U_D is based on the relation:

$$U_D = \frac{dQ}{dt} \times R_e \tag{1}$$

Where Q is the generated charge, dt is the FWHM pulsewidth, and R_e is the amplifier input impedance

The calculated peak amplitudes for a diamond detector of thickness 265 µm, an active area of 7×7 mm^2 , a capacitance of 10 pF, and a corresponding pulsewidth of 1 ns (FWHM) are shown in Table 2.

TABLE 2. Response of a Diamond Detector for Various Source Particles

Particle Species	Generated e-h Pairs	Peak Amplitude
^{241}Am α-particles (5.45MeV) (laboratory source)	4×10^5	3.4 mV
^{12}C (1000 MeV/u)	5×10^5	4 mV
^{238}U (50 MeV/u)	5×10^8	4 V

The quality of today's CVD material makes the collection of about 30–40% of the electrical charge produced by heavy ions possible (3). Figure 2 shows a typical single particle signal obtained with a 10 GS/s single-shot digital storage oscilloscope (DSO) from a diamond detector with a thickness of 330 μm. As expected, the signal is a short pulse of 800 ps (FWHM) width, the risetime is less than 300 ps, and the (1/e-) falltime is 1 ns. The corresponding frequency domain spectrum occupies a bandwidth of more than 1 GHz. Depending on the nuclear charge of the projectile, its mass and the detector thickness, the signal has to be preamplified by a factor between 1 and 1000 to keep the signal level within a 0.1–1 V range for the electronics. In order to maintain the short pulse width, low-input impedance amplifiers have to be used. Careful matching of all transmission lines involved in the signal path is necessary to avoid signal reflections. The detector needs a bias voltage between 100 V and 3000 V DC decoupled from the preamplifier's input.

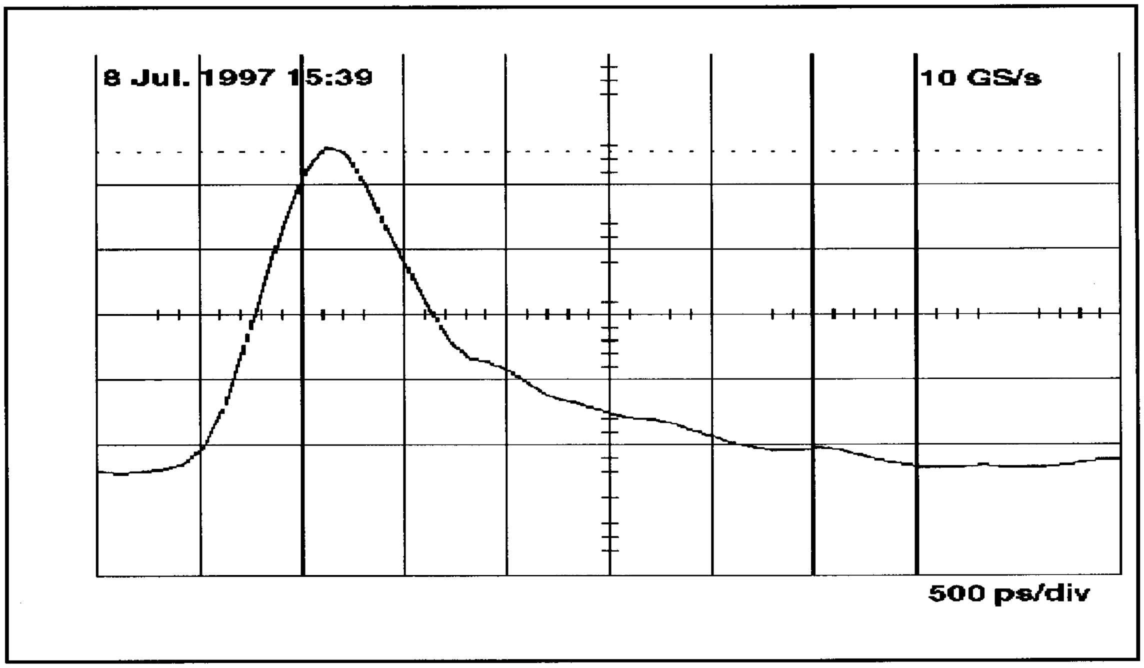

FIGURE 2. Diamond detector signal from a single ^{12}C ion at 200 MeV/u.

Detector Characterization

The short pulse width of the detector signal and the gap between electronic background noise and the lowest amplitudes found in the pulse-height distribution are the important parameters that characterize diamond detectors for beam diagnostic purposes. They define the counting rate capability and charge collecting efficiency.

While the beam intensity inside the synchrotron was observed by a beam current transformer, the extracted ^{20}Ne beam was measured by a diamond detector and simultaneously with an ionization chamber. In the test setup, the diamond detector and the ionization chamber were positioned at right angles to the beam's axis and both were located downstream. The pulses of the diamond detector have been counted using a 500 MHz time interval analyzer. The minimum time interval between two consecutive pulses was limited to 2 ns. The measured count rate was proportional to the beam intensity for rates up to 10^8 counts/s. Beyond this value, the random time distribution of the pulses reached the maximum time resolution of the time interval analyzer's electronics. It could also be observed that the idle count was zero. This zero noise particle counting capability for heavy ions has now been proved for more than 10 diamond detectors.

The pulse height distribution for the diamond detectors clearly shows a gap between background noise and lowest pulse amplitude. Figure 3 shows a typical pulse height distribution of a diamond detector with lead ions at 1 GeV/u used as projectiles.

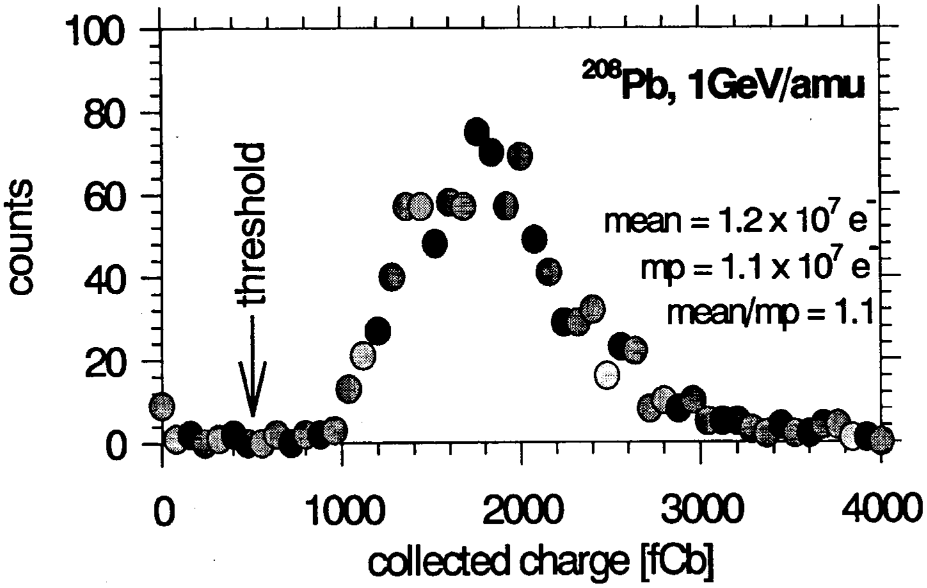

FIGURE 3. Pulse height distribution of ^{208}Pb ions in a 265 μm thick diamond

The improvement of the fast broadband amplifiers enabled us to characterize all diamond detectors with 5.45 MeV alpha particles. For more details on the characterization progress, see (4).

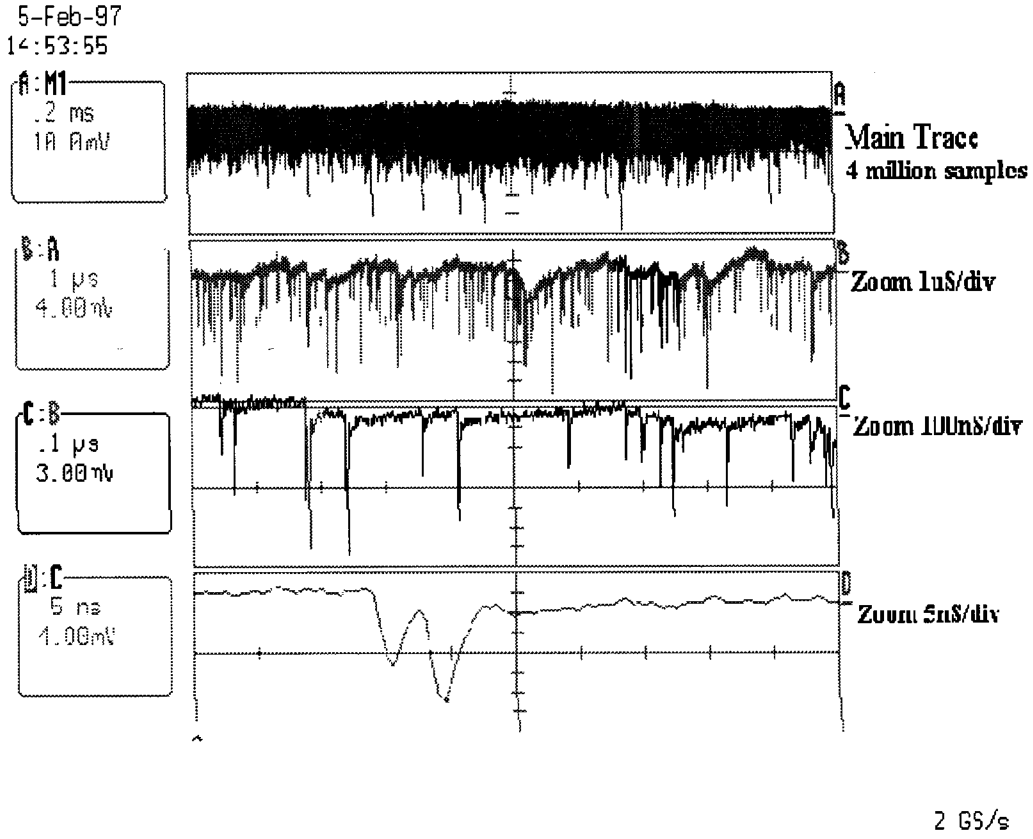

FIGURE 4. Carbon ions of 200 MeV/u from SIS passing a diamond detector. Traces B,C, and D are zooms of the 4 million data points of Trace A. Bottom trace (5 ns/div) indicates single particles.

Beamline Diagnostics

Heavy ions of more than 50 MeV/u passing a diamond detector undergo energy losses of approximately 1–2%. Thus, diamond detectors of 30–500 µm thickness permit transmission mode operation.

In a measurement shown in Figure 4, carbon ions of 200 MeV/u have been recorded with a diamond detector and a fast digital storage oscilloscope (DSO) (5,6). The registered particle count rate reached 10^8 particles/s. Even at the highest count rate, each particle could be registered with good time accuracy. Using mathematical signal processing, the spill structure in time and frequency domain could be analyzed.

Current Developments to Build a Complete Measurement System

The present work focuses on the development of segmented devices with a total active area of 30×30 mm^2. Figure 5 shows actual detector metalization layouts. The one being segmented into 8 parallel strips will be operated with fast 2 GHz electronics, and will increase the total count rate to beyond 10^9 particles/s. The 4×4 pixel detector with 20×20 mm^2 is also ready to use. Both detectors will be arranged together on a mechanical support that is moveable into the extraction line of the SIS. These diamond detectors are not only suitable to measure the intensity but also to obtain dynamic profiles of the particle beam.

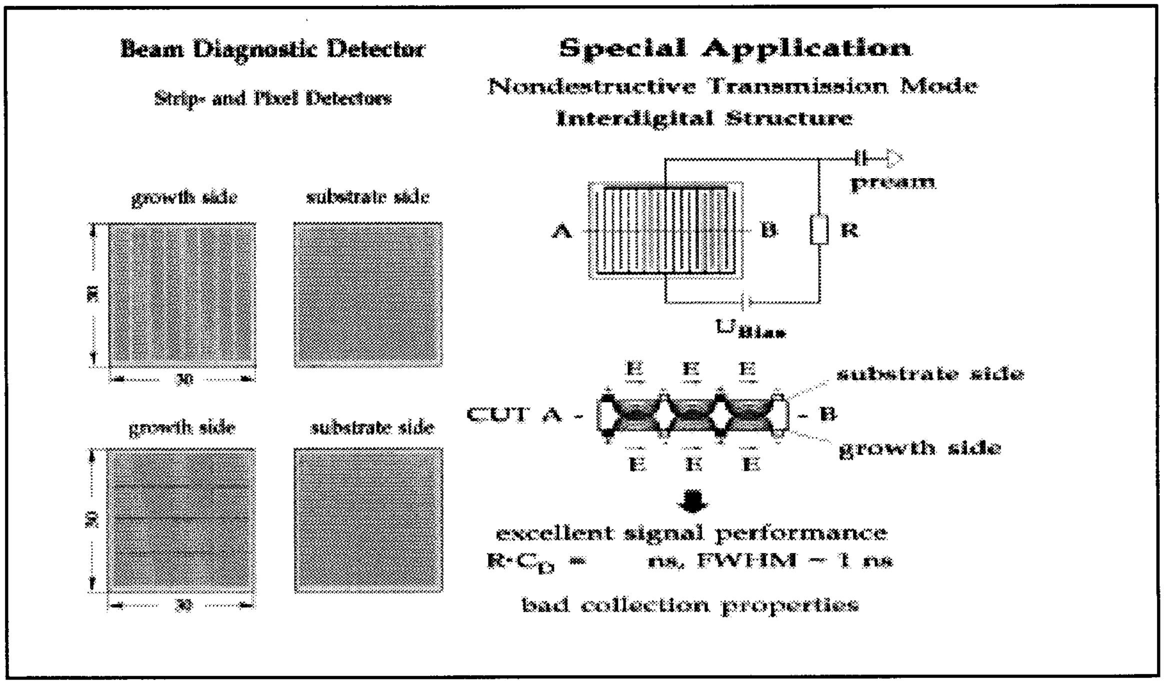

FIGURE 5. Strip , Pixel, and Interdigital Detector layouts.

CONCLUSIONS

CVD-diamond detectors

- are radiation hard devices
- allow big detector areas (presently up to a 4" wafer)
- can be metalized with any desired shape
- are easily assembled (just metalize and apply electrical contacts)
- can be wire-bonded
- are very fast detection devices

- can be operated as noise-free particle counters for heavy ions and alpha particles
- exhibit a wide counting range up to 5×10^8 particles/s per detector segment
- do not require electronic range switching when used together with scalers

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