DIAGNOSTIC SCHEME FOR THE HITRAP DECELERATOR

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Abstract

The HITRAP linear decelerator currently being set up at GSI will provide slow, i.e. keV/u, highly charged ions for atomic physics experiments. Produced at 400 MeV/u the ions are then slowed down in several stages by inversely operated IH and RFQ accelerator structures. To optimize phase and amplitude of the RF systems the intensity, bunch length, and kinetic energy of the particles need to be monitored. The longitudinal bunch length as well as the energy of the beam is usually measured by capacitive pickups. First test experiments show that pickups do not work for the mixture of low intensity decelerated and high intense primary beams, which we face. This contribution describes the construction of new diagnostics, sensitive to low energy and low intensity beams. A fast CVD diamond detector working in single particle counting mode was found to be an excellent tool for monitoring of bunch time structure. The energy of the decelerated fraction of the beam behind the first deceleration cavity was determined to about 10 % accuracy with a permanent dipole magnet combined with a position sensitive MCP detector.

INTRODUCTION

For a number of precise atomic physics experiments highly charged ions (HCI) at rest are very interesting systems. In order to produce them, a 400 MeV/u ion beam is passed through a metal foil. The 400 MeV/u beam is prepared at the accelerator complex of the GSI Helmholtz Centre for Heavy Ion Research in Darmstadt. To meet the experimental needs - heavy, highly charged ions with an energy spread of 1 eV and kinetic energy of a few keV - the HITRAP linear decelerator is currently being built to decelerate and cool the initial 400 MeV/u ion beam. The ions are first decelerated in the Experimental Storage Ring (ESR) from 400 to 4 MeV/u, cooled and extracted in a 1 µs bunch. The beam phase space is matched to an interdigital drift tube (IH) structure in a Double Drift Buncher (DDB), decelerated in the IH from 4 to 0.5 MeV/u and sent to a radio frequency quadrupole (RFQ) which reduces the energy to 6 keV/u. Finally, the HCI are cooled in a Penning trap down to approximately 4 K. The expected beam intensity is up to 10^5 ions in highest charge states as for instance bare uranium [1].

The HITRAP decelerator is working at 108 MHz. To optimize phase and amplitude of the different RF systems one needs to monitor intensity, transversal beam shape, bunch length and energy of the beam. Faraday cups with a fast read out are used to monitor the intensity of the beam along the line. Fluorescent YAG screens observed with CCD cameras show size and the shape of the beam. The bunch length that we need to fit into IH and RFQ structures is about 2 ns, which is typically observed by capacitive pickups eventually averaging over a few bunches on a fast oscilloscope. At the same time the signal from two successive pickups gives information about particles energy using time-of-flight method. An overview of conventional diagnostics installed at HITRAP is given in [2].

However, capacitive pickups do not work for intensities below 0.5 electrical µA peak current or for beams with a large energy spread. Energy measurements by capacitive pickups are seriously limited by the presence of intense beams of different energies after the first decelerating structure. This renders tuning of the IH-structure impossible. Consequently, additional diagnostic devices have been developed for bunch length and energy measurements.

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BUNCH LENGTH MEASUREMENTS

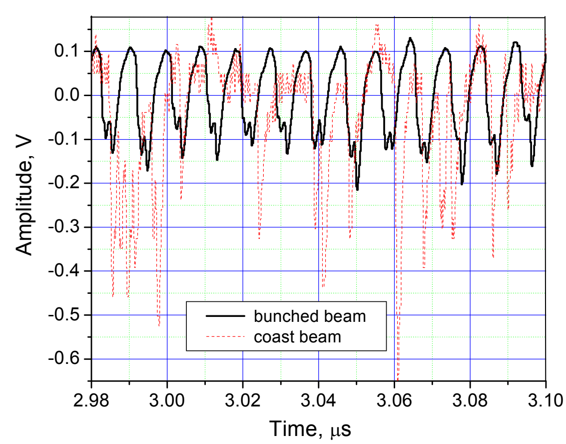

Figure 1: Signal from the polycrystalline diamond detector. The solid line shows the bunched beam, the dashed line the beam without bunching.

A polycrystalline (PC) diamond detector produced by chemical vapour deposition (CVD) to about 15 µm thickness was used for the bunch length measurements. Radiation hardness of the diamond allows the usage of this detector directly in-beam without fast degradation of its properties [3]. Special efforts were taken for impedance matching of the detector, cable and electrical feedthrough. A detector response to a single ion with a FWHM below 2 ns and a rising front of 500 ps was achieved limited by the preamplifier. The signal amplitude of the polycrystalline diamond detector does not depend linearly on but corresponds to the number of incoming ions. Figure 1 shows an example spectrum on the polycrystalline diamond detector of a measurement after the Double Drift Buncher (DDB). The red dashed line shows part of the macro bunch without bunching RF applied to the DDB. The black solid line is the average of 8 macro bunches and demonstrates a clear, regular picture of the bunched beam. Double peaks on the black trace indicate a not yet optimum phase match for the two stages of the DDB.

Polycrystalline diamond detectors are a good alternative to capacitive pickups for measurements of bunch microstructure in case of low- and medium-intense ion beams. The only drawback is that the beam is destroyed by the measurement.

BEAM ENERGY MEASUREMENTS

To decelerate the beam from 4 MeV/u down to 0.5 MeV/u an IH-structure constructed according to the KONUS beam dynamic conception [4] was built. Tuneable output beam energy, compactness, easy operation, and modest RF power requirements are the advantages of such a design if compared to conventional resonant structures. If operated as a decelerator it turns out that most particles are transported efficiently regardless of their energy. Hence, the complete beam leaving the IH is a mixture of several energies from the primary 4 MeV/u to the fully decelerated 0.5 MeV/u with admixtures of partially decelerated ions. The signal on the capacitive pickups is therefore a folded signal and not easy to interpret. Since time-of-flight measurements rely on the selective identification of the same peak on two different pickups it is hard to determine the beam energy this way.

A suppression of non-decelerated beam components would require significant modification of the beam line, hence, an energy selective detector had to be conceived. To fit into the available space it needs to be compact and easy to handle. The energy acceptance of the downstream RFQ decelerating structure is in the order of 5 %, which is then the required detection accuracy.

Single Crystal CVD

A single crystal (SC) diamond detector demonstrates a good linear relation between output voltage and deposited energy, comparable to germanium or silicon semiconductor detectors [3]. Figure 2 shows spectra from a single crystal diamond for different beams. The lower graph shows the spectrum taken without RF field in the IH, so only 4 MeV/u particles are present. The upper graph contains the spectrum with IH switched on, and particles with all possible energies between 0.5 MeV/u and 4 MeV/u are present. Every single peak represents one detected ion. The area of the peak is directly proportional to the energy deposited by the stopped ion.

Sequences for different IH amplitude and phase settings were recorded. In order to exclude pile-up effect only clear single peaks were taken from these spectra to analyze their area.

Several problems have been encountered during the operation of the single crystal diamond detector. It was necessary to drastically reduce the primary beam intensity to avoid pile-up effects. Consequently, 15 shots were necessary to get enough statistics for every setting of the IH equivalent to about 15 min accumulation time. Different peak shape for ions of the same energy (see Figure 2) complicates an on-line analysis. Variable background which also depends on the beam intensity adds more complication. The single crystal diamond was degrading visibly. The charge collection efficiency of the created charges became smaller than one and got different for different energies of incoming ions.

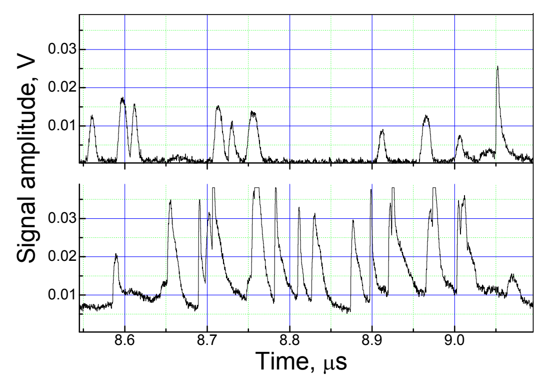

Figure 2: Signal from the single crystal diamond detector. In the upper graph the RF field of the IH was switched on; in the lower graph the IH RF was switched off.

In summary, the accuracy of the energy determination becomes rather limited and the tuning got tedious and long. The relative error of peak area determination, i.e. energy measurement, is above 20 %.

Dipole Magnet – MCP Combination

In order to ease the tuning of the IH-structure in combination with the DDB and to achieve the required accuracy a "one-shot" energy analyzer was developed [5]. A compact permanent magnet bends the beam according to its energy. Horizontal slits in front of the magnet are imaged to the detector plane which is about 135 mm away from the centre of the magnet. The magnetic field of 0.5 T over 45 mm creates a displacement of about 15 and 4 mm at the detector position for A/q = 2.5 beam at 0.5 and 4 MeV/u, respectively. A micro-channel plate (MCP) and phosphorous screen in combination with a CCD camera gives single ion sensitivity.

The typical result of a single-shot measurement is presented in Figure 3. The colour map background is the CCD camera image in false colour mode. From the 2D intensity distribution a projection by summing all data along the vertical direction has been calculated. Off-line calibration of the detector was made to assign the displacement of the peak to the beam energy. The detector has better resolution for slower particles. When comparing peak areas one finds that about 30% of the beam detected after the IH is slowed down to 0.5 MeV/u.

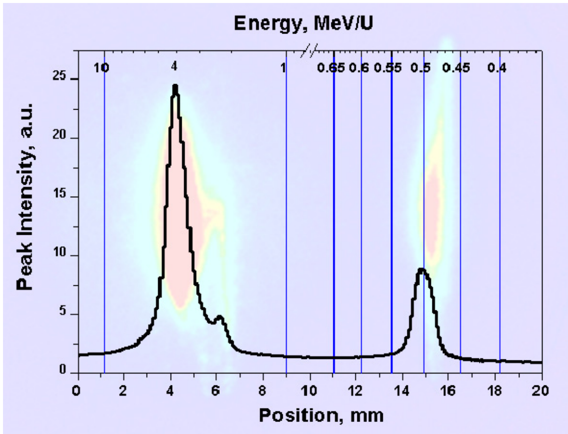

Figure 3: Typical energy spectrum of the ions after IH. Original picture from CCD camera is shown in false-colour-mode together with its projection to the X-axis.

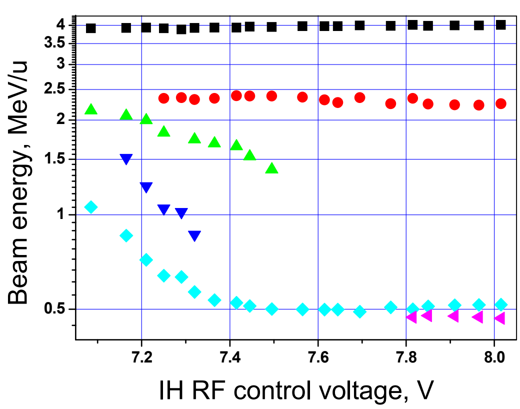

Figure 4: Energy spectra of the ions coming out of IH depending on RF amplitude for a fixed phase of 235°. Black squares shows primary beam, cyan diamonds trends continuously down to the design energy of 0.5 MeV/u. Blue circles, green up-side triangles and blue down-side triangles stand for particles with variable intermediate energy.

The perfect matching of the energy of particles decelerated after IH-structure to the acceptance of the RFQ, the next decelerating stage, is critical. In a small range the IH output energy can be adopted by changes in IH RF amplitude, and DDB phase and amplitude. This has to be used to match the beam into the RFQ and will be monitored with the described detector system.

An example for a scan of the IH structure RF amplitude is shown in Figure 4. Several components of the beam after the IH are analyzed separately ignoring the intensity differences. The energy of the primary beam is not affected by the different RF amplitudes in the IH-structure. Insufficient RF power of IH results in output energy of the decelerated beam ~ 1 MeV/u. Increment in the RF control voltage brings energy down to required 0.5 MeV/u. Particles with intermediate energies appear and fade out with different levels of the IH RF power. Satellite to 0.5 MeV/u peak appeared at very high RF power settings.

The present accuracy of the energy measurements is in the order of 10 % at 0.5 MeV/u and mainly limited by position-to-energy calibration. Furthermore, since beam steering by IH structure is energy dependent, beam fractions with differing energies enter the dipole magnet with different angles, which creates a systematic uncertainty.

To improve the measurement accuracy, an on-line calibration system is being added for in situ calibration and an additional slit system is installed to reduce the angular uncertainty. Finally, an energy measurement with 1 % relative uncertainty will be possible.

CONCLUSION AND OUTLOOK

We have demonstrated new approaches for beam parameter measurements for conditions under which usual diagnostics fail. Polycrystalline diamond detectors demonstrate excellent timing properties suitable for longitudinal bunch microstructure visualisation. A combination of a compact dipole magnet, a micro-channel plate, a phosphor screen and a CCD camera delivers spatial separation of the mixed energy beam and determination of the complete energy spectrum in one shot. Presently the energy of the decelerated particles can be measured with a relative uncertainty of about 10%.

A slit system added together with an on-line calibration system will reduce the uncertainty to about 1%. A similar energy analyser adjusted to the lower energy is installed after the RFQ and will be used for commissioning of the final part of the linear decelerator. The dipole magnet strength of 0.1 T and detector geometry is chosen for spatial separation and detection of 6 keV/u beam.

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