DEVELOPMENT OF AN ION BEAM ANALYSIS SETUP AT THE BONN ISOCHRONOUS CYCLOTRON

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Abstract

The Bonn Isochronous Cyclotron provides light ion beams with a charge-to-mass ratio $Q/A \geq 1/2$ and kinetic energies below 14 MeV per nucleon to one of five experimental sites. It is planned to extend the facility's analytic capabilities through the development and installation of an ion beam material analysis setup. It is intended to use low energy alpha particles with energies between 2 and 5 MeV, with investigations currently under way on whether to achieve this through a higher harmonics operation mode of the cyclotron or energy degrading elements in the beamline.

The analytic methods will be RUTHERFORD backscattering (RBS), which is a method sensitive to the mass of a nucleus, and particle induced X-ray emissions (PIXE) which is used to detect characteristic X-ray emission lines to disambiguate isobars. The experimental setup is currently in development and will house a surface barrier detector (SBD) for RBS, a small number of SBDs for beam characterization and a silicon drift detector for PIXE measurements.

This contribution will give an overview over the development, some preliminary detector tests and a preparatory benchmark X-ray measurement.

BONN ISOCHRONOUS CYCLOTRON

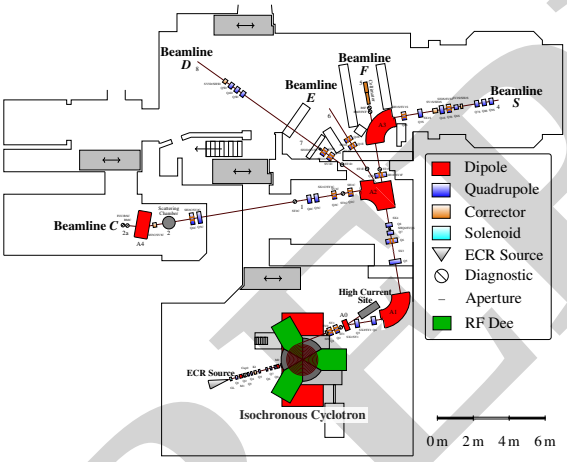

Figure 1: Overview of the accelerator facility.

The accelerator facility of the Bonn Isochronous cyclotron (BIC), shown in Fig. 1, can provide light ions, like protons, deuterons or alpha particles with a kinetic energy of 7 to 14 MeV/A to five experimental sites.

The ion beam is generated by two electron cyclotron resonance sources and directed through a low-energy beamline below the cyclotron and is then injected vertically into the machines magnetic center using an electrostatic hyperboloid inflector. The BIC is an isochronous, three-sector, azimuthally-varying field cyclotron and shows a 120°-symmetry in its azimuthal magnetic field pattern due to its magnet yoke being separated into three hill-and-valley sectors with 0° spiral angle. In each valley, a broadband dual-gap dee is located, providing an acceleration voltage of up to 40 kV. The beam is extracted to a field-compensated channel in a single-turn extraction, using an electrostatic septum [1, 2].

The extracted beam can either be guided to the high current site, used to produce induced radioactivity in target material, or it is transported to the experimental sites via the high-energy beamline [3].

Low-Energy Operation

The BIC, with its three dees, is commonly operated in the third harmonic ($h = 3$) of the ion revolution frequency ω_{ion} within the cyclotron, meaning the RF frequency

$$\omega_{\mathrm{RF}} = h \cdot \omega_{\mathrm{ion}}.$$

As energy gain is directly connected to the magnetic field strength B and the extraction radius R within the cyclotron. Lowering one of them results in a lower achievable energy E_{ion}, with [4]

$$\frac{E_{\mathrm{ion}}}{m} = \frac{\omega_{\mathrm{RF}}}{2h^2} R^2,$$

where m is the mass of the accelerated ion with charge number z_{ion}, and h being the integer value of the harmonic. Because RBS has a cross section which is proportional to $z_{\mathrm{ion}}^2/E_{\mathrm{ion}}^2$, the third harmonic will not be sufficient as it provides alpha particles $\geq$ 28 MeV. Therefore the ninth harmonic ($h = 9$) becomes of interest as it has an alpha particle lower energy bound of 1/9 that of the third harmonic, which is roughly 3.1 MeV.

An alternate path to achieving 2 to 5 MeV alpha particles is by using degrading elements such as foils to energetically reduce the average beam energy early in the high-energy beamline and to subsequently use the dipole magnets A2 and A3 (comp. Fig. 1) to reinstate some of the energy resolution to affect the resulting measurements as little as possible.

First investigations on the operation of the ninth harmonic mode were conducted. Connected to those were studies regarding maximization of the cyclotron's transfer efficiency.

ION BEAM ANALYSIS EXPERIMENT

The currently vacant experimental site at beamline D (comp. Fig.1) was chosen to be used for the ion beam analysis experiment "Bonn Analysis Setup using Ions from the Cyclotron" (BASIC).

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The experiment will employ two techniques, one being Rutherford backscattering (RBS) and the other particle induced X-ray emission (PIXE), to investigate thin films and surfaces of materials, ranging from mono-elemental compounds to ceramics and organic material [5].

In the experiment an ion beam, preferably alpha-particles, with energy $E_{\mathrm{proj}}^{\mathrm{inc}}$ will impinge on a target within a vacuum chamber. Here, they scatter and exit the target with the energy $E_{\mathrm{proj}}^{\mathrm{scat}}$. The incoming and outgoing energies of the ions are connected through the kinematic factor $\kappa(\theta, \lambda)$ via [6]:

$$E_{\mathrm{proj}}^{\mathrm{scat}} = \kappa(\theta, \lambda) \cdot E_{\mathrm{proj}}^{\mathrm{inc}}.$$

This factor κ depends on the angle θ under which the ion exits the target (usually $\theta \geq 135°$) with respect to the beam axis and the ratio λ of masses of the incident ion and the scattered atom in the target

Several simulations of RBS spectra were performed using SimNRA (see Fig. 2). Here, the target was a structured sample with silicon, nickel and gold patches on a carbon matrix. Because of the kinematic factor's dependence on λ one can use RBS to distinguish lighter atoms better than heavier ones while not being able to disambiguate isotopes of equal mass but different charge number. For those two reasons, an additional technique is employed: PIXE.

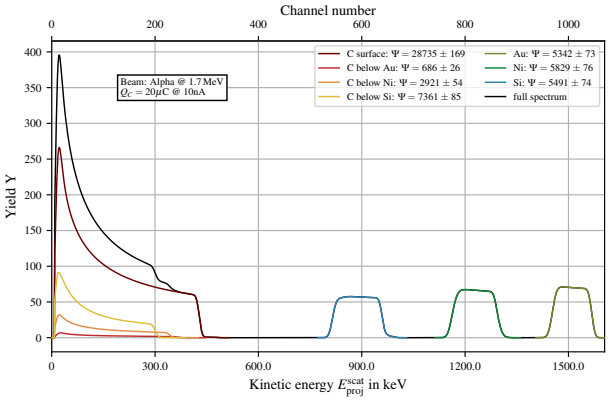

Figure 2: RBS spectrum of a structured sample using SimNRA.

In PIXE collision induced excitations and their subsequent relaxations of shell electrons in the sample are used to identify elements through their characteristic X-ray emissions.

Through a combination of detector efficiency and choice of window material, X-ray photons below a certain energy threshold will not be detectable, limiting the capabilities to high-Z elements.

Applying these two techniques together provides a comprehensive way to analyse samples and identify elements even at trace-amount levels.

Experimental Setup

For the realisation of the experiment a vacuum chamber is imperative as energy loss of ions and attenuation of X-ray photons in air are to be minimized to ensure the detection of sufficient scattering events within a reasonable measurement duration and reliable energy measurements respectively. For compatibility with existing infrastructure as well as for stability reasons, it will be made from stainless steel.

The chamber which is to be manufactured in the near future is shown in Fig. 3. The numerous colored ports relate to different purposes (e.g. light blue for the beam pipe or green for the PIXE detector). It will further be equipped with two lids and a two-axis goniometer on the inside to position the samples into the ion beam. Targets can then be loaded into the chamber via an access port (large, silver port on the right in Fig. 3).

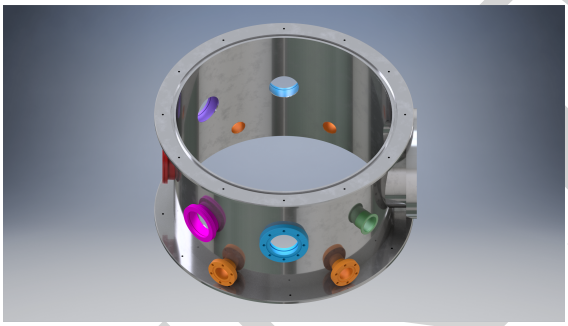

Figure 3: CAD render of the vacuum chamber designed for the experiment using Autodesk Inventor.

A silicon surface barrier detector (silicon SBD) will be placed at a fixed angle to the beam axis inside the chamber. It will be situated inside the vacuum and connects to the readout electronics via a port on the chamber wall (orange port in Fig. 3). Another silicon SBD will be placed behind the sample and off-axis to the beam to measure the transmitted beam current to use as a reference to normalize against.

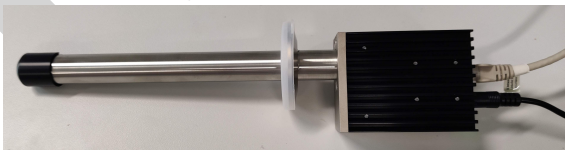

Figure 4: *KETEK AXAS-D 3.0* SDD detector and readout system.

The silicon drift detector (SDD) which will be used in the experiment (see Fig. 4), is located at the end of a long extension (under the plastic cap on the left end) which will be within the vacuum. The readout electronics are directly build into a box (black with cooling fins in Fig. 4) which is on the outside of the chamber (green port in Fig. 3).

Lastly, a new diagnostics section is currently being installed downstream of the Q1D and Q2D quadrupole magnets (comp. Fig. 1), equipped with secondary electron monitoring (SEM), Faraday cup and a beam alignment screen. Simulations into the energy degrading effect of the 0.8 µm SEM foils as well as alternative monitoring options are also under investigation.

DETECTOR CHARACTERIZATION

The two detector types used in the experiment will be an silicon SBD and an SDD. For both of these, a number of

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preparatory steps must be done to prepare for the installation and usage in the experiment.

Surface Barrier Detectors

To assess the available SBDs quality a number of them were subjected to reverse biasing voltage U_B into breakdown to measure their leakage current I_L (see Fig. 5). The fit for I_L comprises a $\sqrt{U_B}$-dependence, similar to a diode behaviour, a linear U_B-term resembling ohmic resistance and a constant offset resulting from temperature induced currents.

For later use in the experiment it becomes essential that the chosen detector only produces a leakage current in the order of nanoampere when operated within the specified biasing voltage regime.

The measurement in Fig. 5 shows a detector well suited for further tests, as it shows a leakage current < 3.5 nA over a wide range of bias voltages.

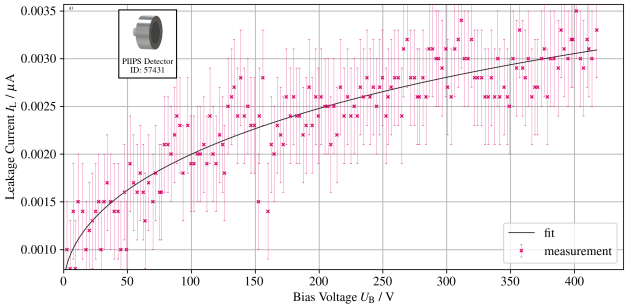

Figure 5: I-V-curve of an SBD for quality assessment.

To measure the energy resolution of SBDs, a formally used radioactive compound source is currently under examination and is expected to be reinstalled in a test setup at the BIC facility.

Silicon Drift Detectors

For PIXE measurements, the *KETEK AXAS-D 3.0*, a combination of SDD and readout electronics, was chosen. To calibrate the detector, a number of measurements were performed. For that purpose, six different elemental sources were irradiated by a 20 mCi Am-241 source, all inside of an *Amersham 2084* source. The characteristic X-rays were detected by the SDD with only a minimal air gap.

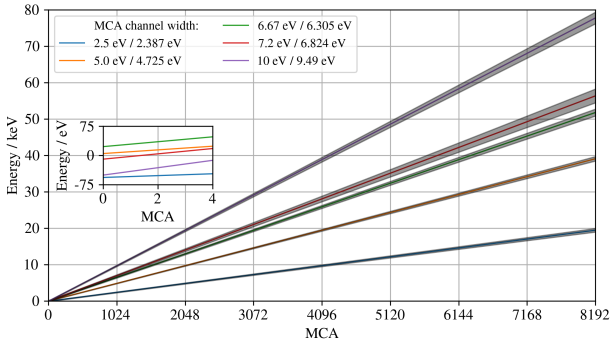

Figure 6: Energy calibration of the SDD for different internal settings.

From these five energy calibrations were fitted (comp. Fig. 6). The value pairs in Fig. 6 are the expected MCA channel width (through the calibration equal to an energy resolution) and the calculated one from the calibrations showing a good agreement with a pure linear relation between energy and MCA channel number. An exemplary spectrum for a silver foil can be seen in Fig. 7.

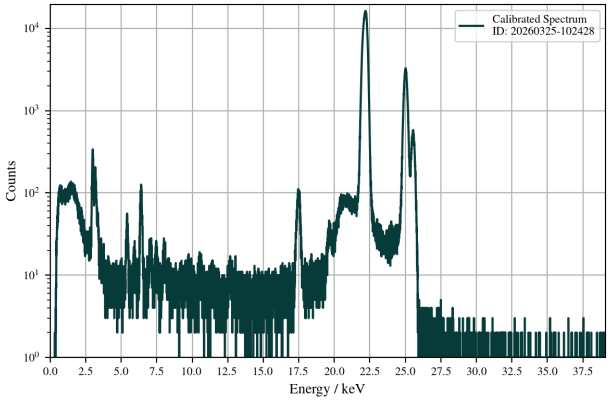

Figure 7: PIXE spectrum of a silver foil with Am-241 incident alpha particles.

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