B.1.7. Target recoil detector

Overall design

The detector for light (target-like) particles is a substantial part of the R3B setup. It allows registration of recoils in coincidence with the heavy fragments, neutrons and the γ-particles. This set-up, therefore, gives a unique possibility to study elastic, inelastic and quasi-free scattering, knockout and breakup reactions. The recoil particle detector provides precise tracking, vertex determination, energy and multiplicity measurement with high efficiency and acceptance. The latter two parameters are very important when dealing with radioactive beams. The general overview of the light ion detector has been described in the R3B LoI [1].

A thick liquid hydrogen target (100 – 250 mg/cm^2) will be used to reach the required luminosity for the radioactive beams. It allows for almost background-free data taking. The use of an extended (3 – 4 cm long) target requires a detector set-up with the possibility to determine the interaction vertex with the precision of 1-2 mm. This precision corresponds to an effective target thickness below 20 mg/cm^2, and allows the energy loss of the recoils in the target to be corrected for.

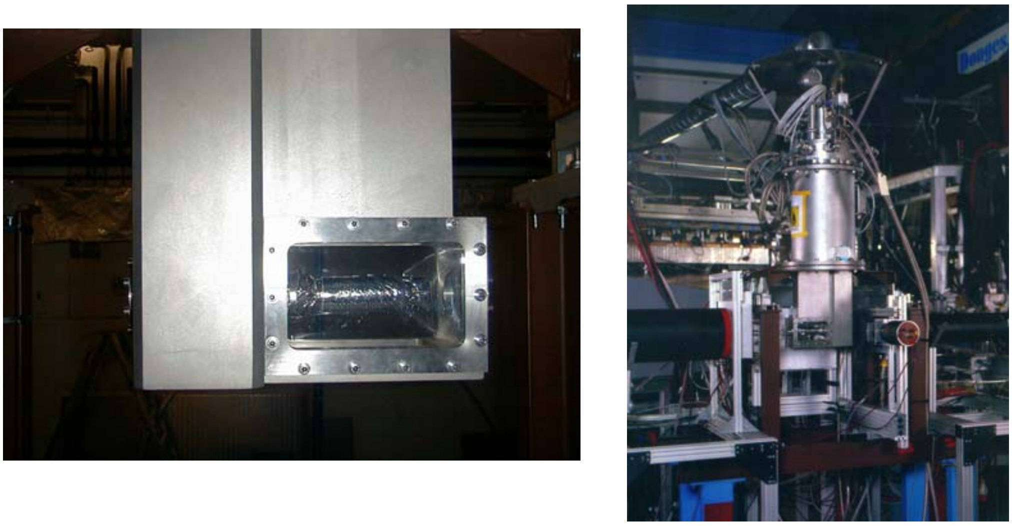

Figure 1.The photograph of the existing liquid hydrogen target.

We will employ a modified version of the liquid hydrogen target that was used for the elastic and quasi-free scattering experiments at GSI [2] (see fig. 1). A new vacuum chamber will be designed. It should be placed in the gamma-particle calorimeter. The calorimeter will cover approximately 75% of the total solid angle with an opening in the backward hemisphere. This space, free of detectors, will be used for the infrastructure of the liquid hydrogen target (tubes, etc.) and the readout electronics of the tracker detectors.

Study of knockout reactions and quasi-free scattering in inverse kinematics requires detection of recoils in an energy-range of 50 – 300 MeV. The typical angular range which has to be covered is 20° to 70° for incident projectile energy of 700 MeV/u. The tracking system consists of two layers of position sensitive detectors. The general scheme of the recoil detector system is shown in Fig. 2.

Detection of the Recoils

The main requirements are high resolution for momentum and energy of the recoiling target-like nuclei. According to previous experience, for the case of (in)elastic scattering, the angular resolution (in centre-of-mass and laboratory system) should be around a few mrad and the resolution in excitation energy, E*, better than 1 MeV.

Some initial simulations have already been carried out that show the feasibility of the system. Extended simulation studies of the performance of the suggested detector scheme should be performed taking into account the size of each individual sensor and the mechanical structure. The simulation package is based on the general purpose transport tool Geant4 [3].

Figure 2. General scheme of the recoil detector. The red cylinder represents the first layer and the green cylinder – second layer of the tracker. γ-detector is shown in blue.

Geant4 can trace particles through various materials, generate other particles according to the interaction cross sections and decay probabilities, as well as to calculate their energy loss and time-of-flight. The analysis of the simulated events is done using the histogramming tool ROOT [4]. The recoil particles are generated using external event generators. The main results of the simulations carried out so far have been obtained for one of the most demanding types of reaction – inelastic scattering.

The aim of the simulation is to find the conditions that optimize the detection system in terms of its tracking capability and detection with good energy resolution and particle identification. In particular the focus is on the following points:

- Distance from the target to the first tracking layer, distance between the layers, thickness of the 1st layer, strip pitch, thickness of the 2nd layer, strip pitch
- Thickness, material and configuration of the vacuum chamber wall
- Thickness and material of the calorimeter
- Energy resolution of all detectors

The key parameters of the detector system are the resolutions in excitation energy and centre-of-mass scattering angle. These values are calculated for a 'standard' detector geometry that has been used as a starting point:

- first layer of Si detectors – 2.5 cm away from the target, thickness is 100 μm, pitch size is 100 μm, energy resolution is 50 keV (FWHM);
- second layer – 10 cm away from the target, thickness is 300 μm, pitch size is 100 μm, energy resolution is 50 keV (FWHM);
- calorimeter – CsI crystals, thickness is 20 cm, energy resolution is 1% (FWHM);
- the wall of the vacuum chamber is 50 μm of stainless steel.

All coordinates and energy losses are folded with the resolutions. The coordinate determination is based on the strip size as in real microstrip detectors. The energy resolutions are based on known test results. The resolution in excitation energy ΔE^* (σ) versus proton recoil energy E_p for the case of inelastic scattering of ^{12}C(p,p') with E = 400 MeV/nucleon is shown on the right panel of Fig. 4. The resolution in the centre-of-mass angle $\Delta\theta$ (σ) versus E_p for the same reaction is shown in the left panel of Fig. 4, resolution on the angle in laboratory system $\Delta\theta$ (σ) versus E_p for the same reaction – in Fig. 5.

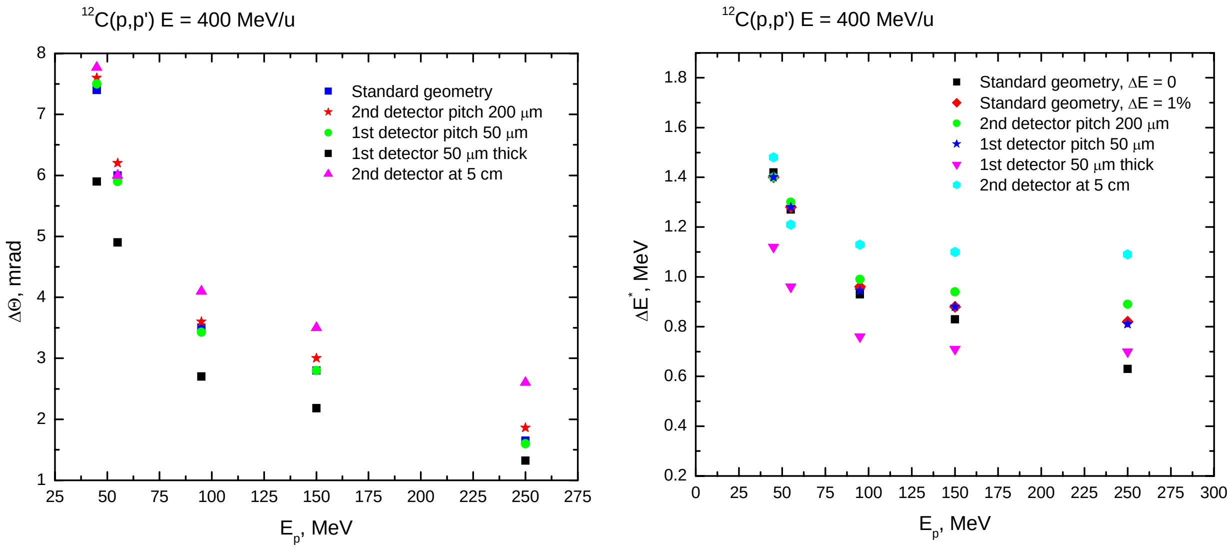

Figure 4. Right panel: excitation energy resolution versus the proton recoil energy E_p for the case of inelastic scattering of $^{12}C(p,p')$ with E = 400 MeV/nucleon. Left panel: resolution on the centre-of-mass angle $\Delta\theta$ (σ) versus E_p for the same reaction.

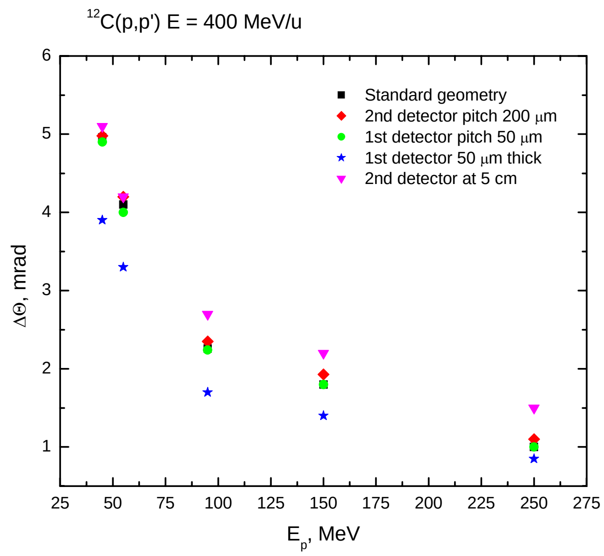

Figure 5. Resolution on the angle $\Delta\theta$ (σ) in laboratory system versus E_p for the case of inelastic scattering of $^{12}C(p,p')$ with E = 400 MeV/nucleon.

The results of the simulations for the higher energy (700 – 1000 MeV) and heavier ions show similar performance. In case of (in)elastic scattering, the required resolution would be $\Delta\theta \leq 3$ mrad (CM angle) and $\Delta E^* \leq 1$ MeV (excitation energy).

First simulations for quasi-free scattering have been performed using an external event generator and the same configuration of the detector as for the inelastic scattering. The reaction chosen is ^{12}C(p, 2p) at beam energy 700 MeV/u. The aim of the simulation was to estimate the accuracy of the separation energy E_{sep} measurement for the given energy resolution of the calorimeter and the given pitch size of the tracker. An example of the ΔE_{sep} calculation for E_{sep} = -15.8 MeV is shown in Fig. 6.

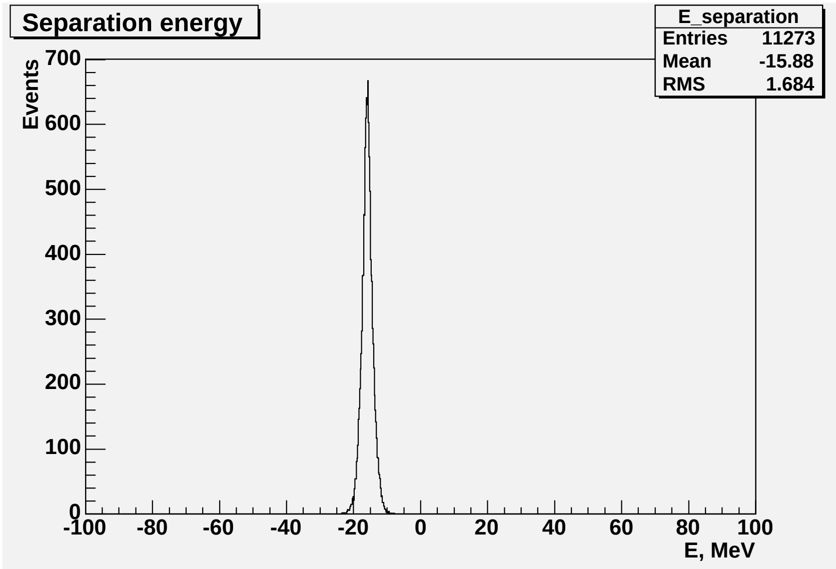

Figure 6. Separation energy resolution for the QFS reaction $^{12}C(p,p')$ with E = 700 MeV/nucleon.

Some results for ΔE_{sep} are presented in a Table 1. One can see that with the designed energy and position resolution the accuracy of the order of ΔE_{sep} = 2-3 MeV is reachable and it will be enough for most of the quasi-free scattering experiments. The precision of the transverse momentum distribution of the cluster p_x is an important observable to show the performance of the system. We can reach Δp_x = 3-4 MeV/c and relative momentum resolution ~ $3\text{-}4 \cdot 10^{-4}$ for the present geometry that is compatible with the performance of the high resolution spectrometer. At the present stage, the simulations of the observables for the quasi-free scattering have been made without Geant4 using separate programs. Multiple scattering was not taken into account but the estimations show it will increase the values of ΔE_{sep} and Δp_x by 30-40%.

Table 1.

Strip size, mm	Energy resolution, %	ΔE_{sep}, MeV	Δp_x, MeV/c
0.01	0.5	0.5	0.5
0.05	0.5	2.1	2.1
0.05	1.0	2.2	2.2
0.1	1.0	4.0	3.5
0.1	3.0	4.1	3.7

The first conclusions are the following:

- ✓ The first layer should be placed close to the target. It improves the precision of the vertex determination and reduces the size and cost of the system. For the time being we consider the first layer of 50 µm thick detectors at 2.5 cm distance from the centre of the target. 100 µm thick detectors would introduce larger multiple scattering, but could be used if the lowest energy of the recoiling protons is about 100 MeV. The individual detectors are arranged to form a barrel with a length of 13 cm, surrounding the target.
- ✓ The second layer, made from 300 µm thick sensors, can be positioned at a distance of 5 cm from the centre of the target. The detectors will be fixed on 17 cm long ladders with the electronics on one side to reduce the dead zones.
- ✓ Energy resolution of the calorimeter for the proton's detection can be 3% (FWHM) without large influence on the overall performance.

An example of this ladder is shown in Fig. 7. The maximum active area of the first layer is about 200 cm^2 and of the second one about 500 cm^2; in the real situation it will be smaller due to the infrastructure of the target and a mechanical arrangement of the individual sensors. The exact geometry of the calorimeter (which is simultaneously used as the γ-ray detector, see **B 1.5**) and the crystal type – CsI, NaI or $LaBr_3$(Ce), will depend on the results of the detailed simulations (including segmentation of the calorimeter, dead zones etc.) and the tests of the prototypes. In general, the scheme described above should fulfill the requirements.

A possible solution for the first layer of the tracker is double-sided Si detectors (DSSDs) but such detectors are normally thicker – 200 μm or more. Thinner sensors (30 – 100 μm) with a reasonable size of 20 – 25 cm^2 are commercially available (Micron Semiconductor). This solution requires some R&D and prototyping to prove the performance of such thin detectors. The advantage of this solution is the moderate number of readout channels (40k or less) and the experience gained by several high-energy experiments [5, 6, 7]. In any case, additional simulations should be made including realistic rates of all reactions. If the probability of getting two hits in the same strip within the integration time of the front-end chip is large, we need to reduce the strip length or even use pixels.

Figure 7. Example of the arrangement of the double-sided Si detectors on a ladder (a part of the tracker system of the AMS experiment).

Another prominent solution is based on Monolithic Active Pixel Sensor (MAPS) technology [8]. These devices have projected thicknesses down to 30 - 50 μm, single point resolution of 5 μm and an efficiency of 99%. The maximum active size is at the moment ~3 cm^2. R&D in high energy physics is going towards larger area detectors. Two members of the collaboration, namely CEA Saclay and the consortium of UK universities, participate in this R&D. An example of the detectors made on a 6” wafer is shown in Fig. 8.

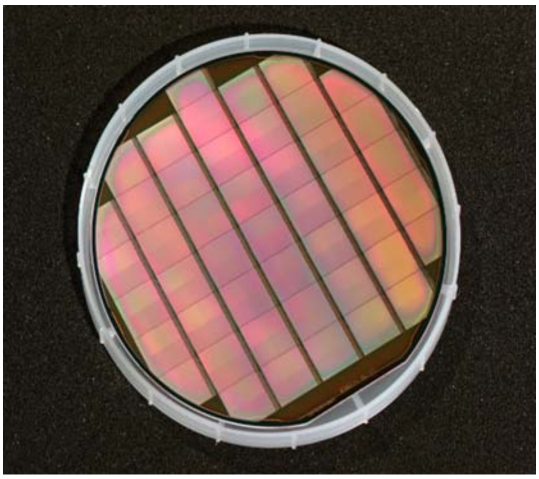

Figure 8. Prototypes of the MAPS detectors on 6” Si wafer.

An attractive feature of MAPS is that they allow a System-on-a-Chip by integrating signal processing micro-circuits (amplification, pedestal subtraction, digitization, and discrimination) on the detector substrate. The resulting chip may be thinned down to a few tens of microns. There is extensive R&D going on with the aim to use MAPS as the vertex detector in the CBM experiment [9] and in other future experiments in nuclear and high energy physics.

Another solution for the first layer is the Image Sensor with In-situ Storage (ISIS) pixel detector that is being developed for the future linear collider [10]. It is based on CCD technology and the existing prototypes already have a size of 10 cm^2 (Fig. 9). The arrangement of sensors mounted on a ladder also fits the geometry of the first layer. The position resolution of ISIS can be of the same order as MAPS (~5 μm) and there is no problem to make larger pixel sizes. This detector can also be made 30 μm thick [10]. The drawback of the MAPS or ISIS detectors is, of course, the large number of pixels (~ 2×10^6) that requires a special readout scheme. The energy loss measurement might be difficult using such thin sensors. In this case the total energy will be measured by the second layer of the tracker and the calorimeter and corrected for the missing energy in the first layer. Simulations show that the errors, introduced because of this, are very small.

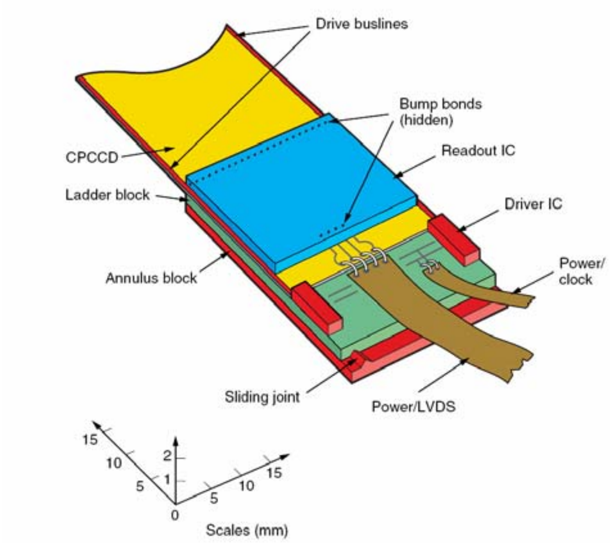

Figure 9. Prototype of the ISIS detector on the ladder.

The second layer of the tracker can be made from double-sided Si detectors with a standard thickness of 300 μm. The number of readout channels for this layer is estimated to be 50k.

There are some considerations about the readout electronics and especially about the front-end chips. On the one hand, a smaller thickness (l) introduces less multiple scattering~ $\sqrt{l}$, less leakage current ~ l and smaller full depletion voltage ~ l^2. One the other hand, the reduction of the detector thickness implies a reduction of the signal-to-noise ratio S/N that depends on the relative contributions from the series (ENC_s) and parallel (ENC_p) noise:

$$S/N = \frac{r_L \cdot S_{300} \cdot (l/300\mu m)}{\sqrt{ENC_s^2 + ENC_{p300}^2 \cdot (l/300\mu m)}}$$

where S_{300} is the most probable charge deposition (for the given energy of the protons) in a 300 μm thick detector and r_L accounts for Landau fluctuations and charge collection deficits. Energy losses in the Si detectors will be between 5 MeV and 150 keV. This implies a dynamic range of 1:30 so it is not very large and many commercially available readout chips are able to handle it. The most difficult situation will be with the first layer of the tracker. Thin detector (50 – 100 μm) is mechanically less stable and S/N ratio is smaller, especially for the fast protons. Taking into account realistic values for ENC_s and ENC_p ~ 700 e^-, we can have S/N ≥ 10 that should be enough for tracking. One should mention that there will be an extensive R&D on Si detectors and their readout electronics within the EXL project. Their requirements are in general higher – the detectors and a front-end electronics are required to work in UHV conditions, a precise time measurement is foreseen, the dynamic range of the signals is higher etc. Nevertheless, if the performance of the detectors and the electronics, developed for EXL, are sufficient and the price is not higher than from commercial sources, we will use the same solutions for R^3B. There will be a permanent exchange of information and ideas between the collaborations.

The readout of analog information from the strips is based on the multiplexers and the serial line for the data transmission. The custom receiver modules are digitizing the amplitudes; the service module SAM with fast DSP in it makes the pedestal suppression and processing data in real time.

Both layers of the tracker will operate inside a vacuum chamber with a radius of about 25 cm. The support structure for the detectors and the readout electronics will be made from carbon fiber. The material is strong enough and has low density. It would minimize the scattering of the particles in the support structure. The cost estimation for the design, prototyping and production of the support is 75 k€.

The Si sensors will be built up on a granite bench and optically aligned before they are bonded into the support structure. Then the alignment of the sensors after mounting will be done using cosmic rays (high energy muons). Both approaches give the relative position of each sensor with respect to the others. The final alignment of the system will be made after mounting it into the experimental setup with the laser metrology system.

The power dissipation of the detectors and the corresponding front-end electronics should be kept as small as possible due to the vacuum conditions. In any case, it will be less than 300 W for the whole tracker system. This will require cooling, but without any cooling media like water or other liquid. The typical consumption of one ADC VME module is on the order of 30 W so the consumption of the VME part, including 5-6 VME crates, can be on the order of 5-6 kW.

Cost estimation

The cost of estimation for the first layer of the tracker is based on the first option that assumes we use DSSDs and the 64-channel readout chip VA_hdr9b (IDEAS). The cost of estimation for the second layer of the tracker is also based on using DSSDs with 200 μm strips and the same readout chip:

Item	**Cost estimation**
Si sensors	81 k€
Chips	162 k€
Capacitors, electronic components	86 k€
PCB, cables	67 k€
ADCs, readout	126 k€
Support structure	75 k€
Sum	522 k€

Total sum (taking into account 10% spare of all components) – 650 k€.

We expect that the cost of the system using MAPS or ISIS detectors in the first layer will not be much higher. Further simulations and tests of the prototypes will be performed with the aim of optimizing the system. One should note that in case some parameters of the existing sensors or chips cannot fulfill the requirements, an extensive R&D will need to be performed which will considerably increase the overall cost.

Radiation hardness

The recoil detector will be used for detecting the secondary particles from nuclear reactions in the target. Taking into account a maximum rate of 10^8 - 10^9 radioactive ions/s and a 1% interaction probability, we estimate a maximum flux for the recoils of 10^6 - 10^7 particles/s for the whole detector system or 10^4 - 10^5 particles/s per cm^2. Assuming typical beam time of 2 months per year, the detector must stand a total dose of up to $5*10^{10}$ particles per cm^2 per year. This dose is much smaller that the estimated doses for the

Si detectors in vertex systems of the LHC experiments, which are typically 10^{14} - 10^{15} charged particles per year [5, 6, 7].

Space requirements

The system will be very compact and fit into the inner part of the γ-ray detector, which is a sphere with an inner diameter of 50 cm and an outer diameter of 100 cm. The support structures will be designed to accommodate either liquid (hydrogen, deuteron, helium, etc.) or solid targets. Additional space of the order of 6-8 m^2 is required for the electronic racks.

Test experiments

The collaboration has already purchased several Si microstrip detectors equipped with their readout and these will act as the first prototypes of the second layer of detectors. Each detector has a size of 30 cm^2 and a readout pitch of 100 μm on both sides of the sensors. Test experiments using proton and light ion beams are inevitably required in order to prove the simulations and make a decision on the best suitable detector technology. A first test experiment using ^{12}C at 250 MeV/u and lighter nuclei from the fragmentation of ^{12}C has been made in November 2005. The detectors show very good performance in terms of signal-to-noise ratio, energy and position resolution. These prototypes will be used inside the existing LAND-ALADIN setup and will allow valuable experience to be gained. Further tests will be necessary as the new prototypes are developed. The energy of the protons and some light ions should be in the range of 50 - 500 MeV/u. Test experiments using high rate accelerator facilities are foreseen to check the radiation hardness of each prototype.

Milestones

2005 - 2006	Simulations and optimization of the geometry, tests of prototypes
End of 2007	Decision on the detector concept
End of 2008	Preproduction prototypes, concept of installation and alignment
2009 - 2010	Mass production of the detectors and electronics, installation

Working group and personnel

T. Aumann [a], W. Catford [b], M. Chartier [b], P. Egelhof [a], H. Emling [a], M. Freer [b], O. Kiselev [c], J.V. Kratz [c], M. Labiche [b], R.C. Lemmon [b], T. Nilsson [d], G. Nyman [e], E. Pollacco [f], G. Schrieder [d], H. Simon [a], A. Shrivastava [g]

a) Gesellschaft fur Schwerionenforschung, Darmstadt, Germany
b) UK collaboration
c) Institut für Kernchemie, Johannes Gutenberg Universität Mainz, Mainz, Germany
d) Institut für Kernphysik, Technische Universität Darmstadt, Darmstadt, Germany
e) Chalmers University of Technology, Göteborg, Sweden
f) DAPNIA, CEA Saclay, Gif sur Yvette, France
g) BARC, Mumbai, India

In addition to the participants of the working group, some more personnel are foreseen. On average, one or two postdoctoral positions and one or two positions for PhD students will be required in each institution to work on this project. Technical and engineering support will also be necessary.

Our working group includes people from the Universities of Mainz, Darmstadt, Chalmers and GSI who have experience in tracking detector design and simulations. They will be involved in optimization of the calorimeter surrounding the tracker and the tests of the prototypes. The participants from CEA-Saclay have built several detector systems for nuclear physics (MUST, MUST2) and developed front-end ASICs and corresponding electronics. Several UK universities and laboratories participate in the R^3B and EXL projects and have been involved in many experiments in nuclear and high-energy physics. Their MAPS development program is world-leading and they are heavily involved in designing ASICs for both the ATLAS and CMS experiments for the LHC at CERN. They also have expertise in hybrid pixel detectors (sensor bonded directly to ASIC) and in general building blocks such as low noise preamps, shaping amplifiers, multiplexers, ADCs, analogue pipelines (to increase the apparent ADC sampling rate) and detector readout. The R^3B recoil detector is, in many aspects, similar to the one that will be built for the EXL project. Therefore we can profit from the partial overlap of R&D with EXL.

References

1. R^3B LoI, GSI, 2004.
2. F. Aksouh, PhD Thesis, Universitè de Paris XI, Orsay, France, 2002.
3. S. Agostinelli et al., Nucl. Instr. and Meth., A506 (2003) 250.
4. R. Brun and F. Rademakers, Nucl. Instr. and Meth., A389 (1997) 81.
5. CMS The tracker project, Technical Design Report, CERN/LHCC 98-6, TDR 5, 1998.
6. ATLAS Inner detector, Technical Design Report, TDR 5, 1997.
7. ALICE Technical Design Report of the Inner Tracking System (ITS), CERN/LHCC/99-12, ALICE TDR4, 1999.
8. M. Deveaux et al., Nucl. Instr. and Meth., A512 (2003) 71.
9. CBM LoI, GSI, 2004.
10. T. Goji Etoh et al., IEEE Trans ED (2003) 144.