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LYCCA — the Lund-York-Cologne CAlorimeter

Identification of reaction products in HISPEC-DESPEC@NuSTAR

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Objective

LYCCA is an acronym for Lund-York-Cologne CAlorimeter. It is a core device for the HISPEC-DESPEC[1] program, which is part of the NuSTAR[2] collaboration within FAIR[3]. LYCCA is a dedicated NuSTAR and thus FAIR device.
The main objective of LYCCA is to uniquely characterize exotic nuclei by their mass, A, and charge, Z. The nuclei are secondary reaction products following Coulomb excitation, direct reactions, or fragmentation reactions of relativistic radioactive ion beams. These beams are to be provided by the new Super-FRagment Separator (Super-FRS). They will have energies of 100–200 MeV/u when hitting the secondary target in the HISPEC focus of the NuSTAR Low-Energy Cave.
LYCCA is supposed to be a flexible array of detector modules. Each module comprises a set of cesiumiodid (CsI) detectors for the energy measurement of the reaction products and double-sided Si-strip detectors (DSSSD) for energy loss and position information. The measurement of the time-of-flight (ToF) between the target position and LYCCA is ultimately to be performed with polycristalline diamond wafers. During the physics driven LYCCA-0 commisioning phase at the existing FRS (PreSPEC, 2009-2012) and an early implementation phase at HISPEC (2013-2014) the stop signal of the ToF measurement will be backed up by a system comprising a large-area ultra-fast scintillator in conjunction with multiple photomultiplier tube readout.
LYCCA-0 has approved commisioning beam time at the GSI-FRS facility, and as a follow up to the PreSPEC Letter of Intent, a suite of physics proposals will be presented to one of the coming GSI PAC meetings.

[1]HISPEC: High-Resolution In-Flight SPECtroscopy; DESPEC: DEcay SPECtroscopy
[2]NuSTAR: NUclear STtructure, Astrophysics, and Reactions
[3]FAIR: Facility for Antiproton and Ion Research

1 Introduction

1.1 General Considerations

The HISPEC-DESPEC collaboration aims at nuclear structure studies of excited exotic nuclear species far from the line of stability. The specific tool is high-resolution γ-ray spectroscopy based upon Ge-detector arrays, the components of which are highly segmented, i.e., providing not only precise γ-ray energy but also γ-ray detection position information.
In the HISPEC set-up it is vital for the spectral quality and thus sensitivity of the experiments to have as precise information on the energy (relativistic velocity), the position, and the direction of the *moving* sources to match the expected detection capabilities of individual γ-ray interaction points of AGATA[4]. This calls for a device, which must be able to

- track the reaction products in conjunction with detectors at the secondary target position, and
- event-by-event identify the secondary reaction products as well as determine their momenta.

HISPEC-style experiments have been and are being performed at several accelerator complexes in Europe, the U.S., and Japan. At the FRS/GSI facility, such experiments have been done within the RISING[5] Fast-Beam campaign 2003–2005. Here, γ-ray spectroscopy with fifteen former EUROBALL Cluster detectors was used in conjunction with the CAlorimeter TElescope (CATE)[6] responsible for the discrimination of reaction products. Both the experience with CATE and extensive simulations (cf. Sec. 5) within the LYCCA collaboration show that several items are to be considered for an improved HISPEC calorimeter system:

- A physical segmentation of both ΔE and E elements is useful for both rate considerations and active tracking. Through the latter improved energy and consequently mass resolution should be obtained due to straight forward corrections of possible CsI light-collection dependencies on position.
- The finite thickness of the secondary target seriously limited the envisaged mass resolution of CATE – an as sophisticated as possible time-of-flight measurement must be added into the system being a compromise between flight path, i.e., solid angle coverage, and time resolution of the detectors used — a total of significantly better than $\Delta t \sim 100$ ps is considered necessary, though this number does depend also on recoil energies and mass regimes of interest for a given experiment.
- LYCCA should be able to deal with light ions with energies up to some 200 MeV/u, $A \sim 20$, and heavy ions down to about 100 MeV/u, $A \sim 200$.

[4]AGATA: Advanced GAmma-ray Tracking Array
[5]RISING: Rare Isotope Spectroscopic INvestigations at GSI
[6]CATE: CAlorimeter TElescope; R. Lozeva *et al.*, Nucl. Instr. Meth. A562, 298 (2006).

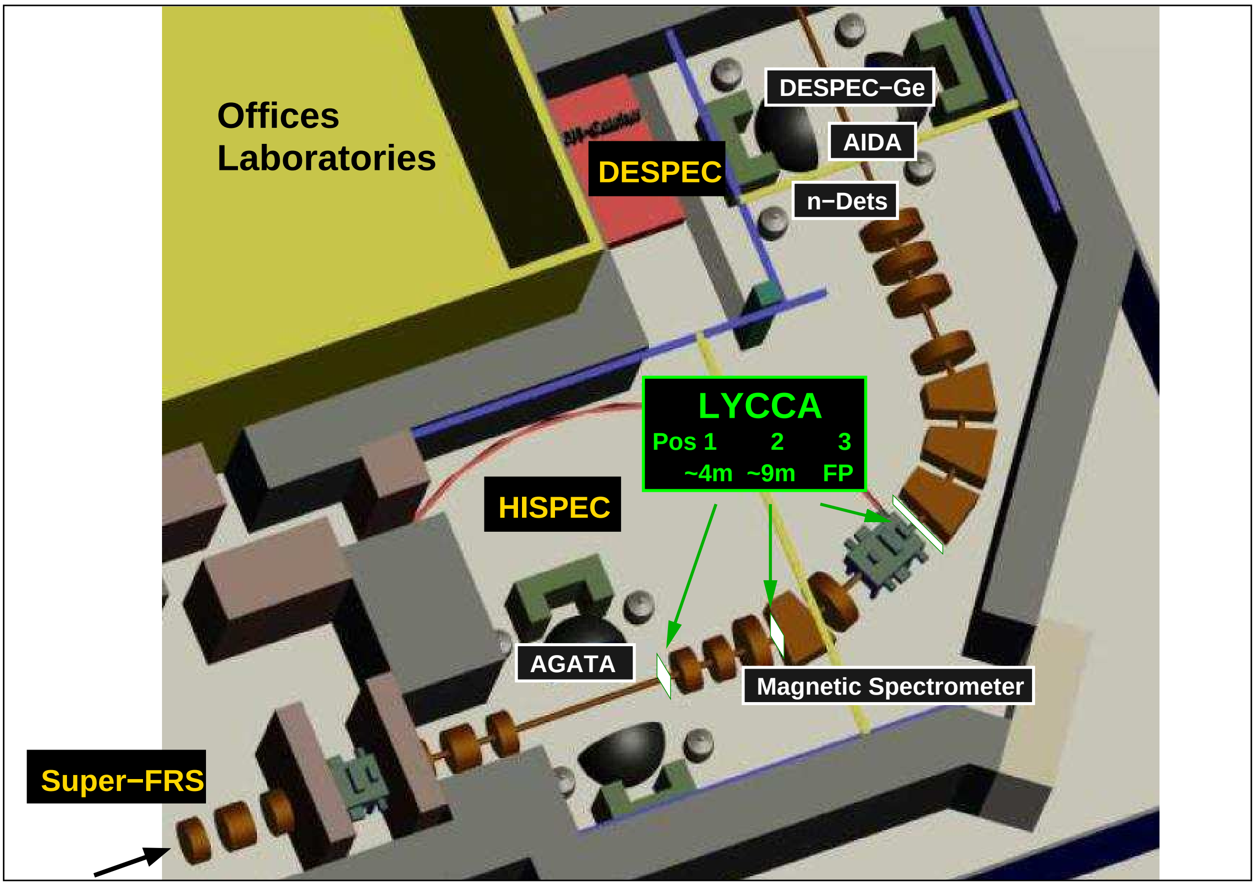

Figure 1: Proposed (03/2007) basic layout of the NuSTAR Low-Energy Branch. Three possible positions are indicated for the *flexible*, i.e., experiment-dependent, placement of certain LYCCA configurations. Position 2 is possible both at an early HISPEC stage (without the magnetic spectrometer) and later with the magnetic spectrometer turned aside.

Figure 1 provides a sketch of the prospected layout of the NuSTAR Low-Energy Cave. It includes tags for key HISPEC-DESPEC instruments and three possible locations for LYCCA: Position 1 is about 4.0 m behind the secondary target and there LYCCA will cover angles of $\Delta\theta \sim \pm 2.0°$. Position 2 is about 10 m behind the secondary target with a coverage of $\Delta\theta \sim \pm 1.0°$. Note that this position is possible both at an early HISPEC stage, i.e., without the magnetic spectrometer being in place, and later with the magnetic spectrometer turned away from the nominal zero degree placement. For both positions 1 and 2 it is envisaged that central elements of LYCCA can be moved to larger angles. This modification (*i*) increases the angular coverage to some $\Delta\theta \sim \pm 3.0°$ (position 1) and (*ii*) allows ions on central trajectories to enter the magnetic spectrometer for high-resolution mass spectroscopy and possibly recoil decay studies in combination with the DESPEC set-up. Position 3 enables A and Z identification in the focal plane of the magnetic spectrometer. Consult Secs. 2,4 for more details concerning specific LYCCA set-ups.
The study of dripline nuclei on the neutron-deficient side demands experimental set-ups, which are not only sensitive to γ-radiation, but also light charged particles, which can be emitted from particle (mainly proton or α) unbound, quasi-stationary states in competition

with γ radiation. Dedicated LYCCA modules arranged in a 'ring' at about 50-60 cm distance from the secondary targets could be used to detect such particles in prompt coincidence with the γ rays. Last but not least, spectroscopic studies of neutron-deficient nuclei benefit largely from detecting those neutrons, which are emitted in the course of the reaction. Eventually, LAND[7] (or some similar device) might be used at the 10-m position for coincident neutron detection and thus 'complete' spectroscopy.

1.2 Basic Requirements

Within the HISPEC-DESPEC collaboration and following consultations with the RISING collaboration a number of possible experiments are to be investigated. They are presented in Table 1. The last two columns provide a rough estimate of the expected energy regimes and thicknesses of DSSSD and CsI elements, respectively. The numbers are based on recent SRIM[8] releases.

Besides these numbers, first simulations concerning A and Z resolution (cf. Sec. 5) indicate the following main characteristics for LYCCA:

Energy resolution (FWHM): $\Delta E/E < 1$ %, projected goal $\Delta E/E = 0.5$ %

Time resolution (FWHM): $\Delta t < 100$ ps, projected goal $\Delta t = 50$ ps

These numbers are initial guidelines and depend strongly on the actual flight paths and the individual experiments, namely the mass regimes to be studied. See Sec. 5 for some examples.

Table 1: Overview of HISPEC reaction types.

Experiment class	Recoil mass (u)	Recoil energy (MeV/u)	Total energy (GeV)	DSSSD energy (GeV)	CsI range (mm)
Electromagnetic excitation	20	200	4.0	0.017	30
Secondary fragmentation	60	155	9.0	0.24	5.0
Coulomb excitation	100	100	10.0	1.1	1.1
Transfer reactions	130	115	15.0	0.9	2.3
Transfer reactions	200	100	20.0	2.4	0.6

1.3 LYCCA Timeline

LYCCA will be produced in four main stages with each stage building upon in-beam tests and physics experiments of the preceding stage. In that spirit, the CATE array from the RISING Fast-Beam campaign is viewed as the existing base line.

Stage 1 is the manufacturing of a single LYCCA DSSSD-CsI module and first in-beam tests, possibly including DSSSD and possibly diamond ToF options.

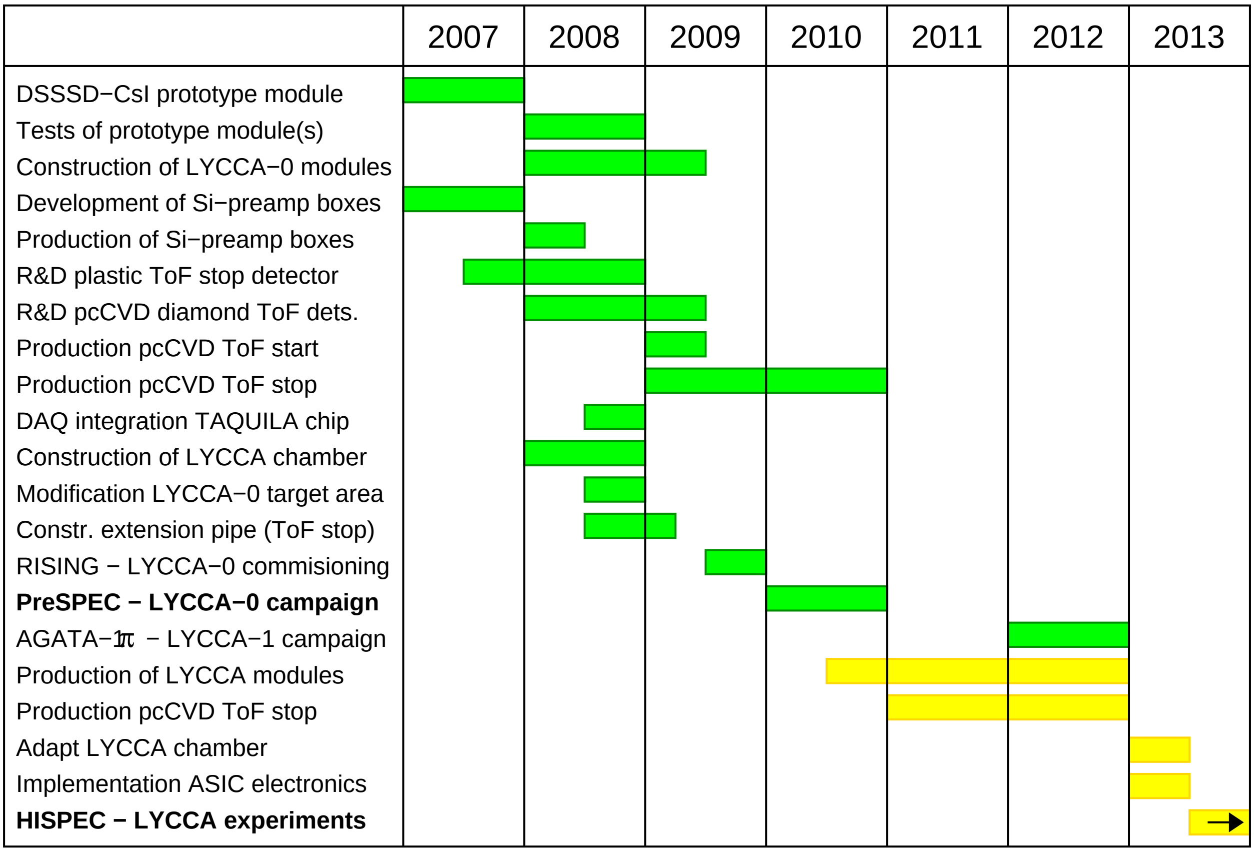

Figure 2: Estimated (4/2008) timeline of the LYCCA project.

Stage 2 is the production of LYCCA-0, which will comprise four central LYCCA modules and eight surrounding LYCCA-CATE(CsI) modules. All new DSSSD and all previously used (CATE) and new CsI detector modules as well as associated electronics do exist for LYCCA-0. The new detectors have been financed through either private Swedish foundations or RISING running costs. First 29 mm × 29 mm sized polycrystalline CVD diamond detectors are presently procured by the University of York and Surrey University at and in collaboration with the spin-off company Diamond Detectors Ltd., UK. Four such detectors will provide the ToF start signal at the secondary target position (2009–), while ultimately nine 19 mm × 19 mm sized wafers are foreseen for each LYCCA module. In the course of PreSPEC (2009-2012) we will implement step-by-step the four central LYCCA-0 modules with such CVD diamond wafers with the progress essentially depending on financial rather than technological issues. A high-quality ToF stop signal for PreSPEC/LYCCA-0 is going to be provided by a large-area fast plastic scintillator, readout by at least eight high-performance photomultipliers. This system, which serves also as backup for stage 3, is currently being commisioned at GSI by a joint GSI-Lund PhD student (see Sec. 2.5.4 for details). LYCCA-0 is to be in-beam commissioned in the second half of 2009 within the

[7] LAND: Large Area Neutron Detector
[8] SRIM: The Stopping and Range of Ions in Matter, J.F. Ziegler and J.P. Biersack

envisaged PreSPEC campaign, starting with the RISING Fast Beam configuration in 2010 towards the use of the AGATA Demonstrator at the FRS S4 Focal Plane (2011-2012). The main issues are physics driven fast-beam experiments while improving the identification of secondary reaction products towards an optimal set-up for HISPEC as far as calorimeter and timing techniques are concerned. The use of LYCCA-0 within RISING and PreSPEC experiments has been positively taken by the RISING Steering Committee (Madrid meeting, November 2006) — LYCCA-0 shall be ready by mid 2009 to allow for first experiments during 2009 and a full experimental campaign in 2010.
Stage 3 implies the move from the S4 area of the existing FRS to the new Low-Energy Cave at the Super-FRS facility and foresees a constant upgrade towards a fully equipped diamond stop ToF system and an increasing number of LYCCA modules (2013-2014). Stage 4 is the full implementation of LYCCA at HISPEC, followed by modules for coincident light charged-particle spectroscopy (2015–).
Figure 2 provides the scheduling of different tasks associated with the four stages. Green slots indicate rather safe estimates, also related to existing and projected funding of the project. Note that the timing of the RISING but in particular the AGATA-Demonstrator experiments depend heavily on the beam-time availability at GSI and the readiness of the Ge-detector arrays. Clearly, the first major milestone in the timeline is the implementation of LYCCA-0 in 2009 and a PreSPEC-LYCCA-0 experimental campaign in 2010. Slots marked in yellow account for uncertainties of not only the funding profile of LYCCA, but mainly external developments related to FAIR, NuSTAR, and HISPEC-DESPEC.

Note that a basic acceptance of this TDR is required by both the Swedish and UK authorities to release the bulk investment money towards LYCCA.

2 Detectors

The LYCCA detectors have to be viewed in relation to existing systems such as CATE and in conjunction with tracking and timing detectors at the secondary target position. Figure 3 provides a schematic drawing of the key components of the coming combinations LYCCA-0 + RISING and AGATA-Demonstrator (PreSPEC campaign) and, finally, 'LYCCA + HISPEC'. Within the staged process outlined above, the ToF measurement between positions 1 and 3 in Fig. 3 will be continously improved.

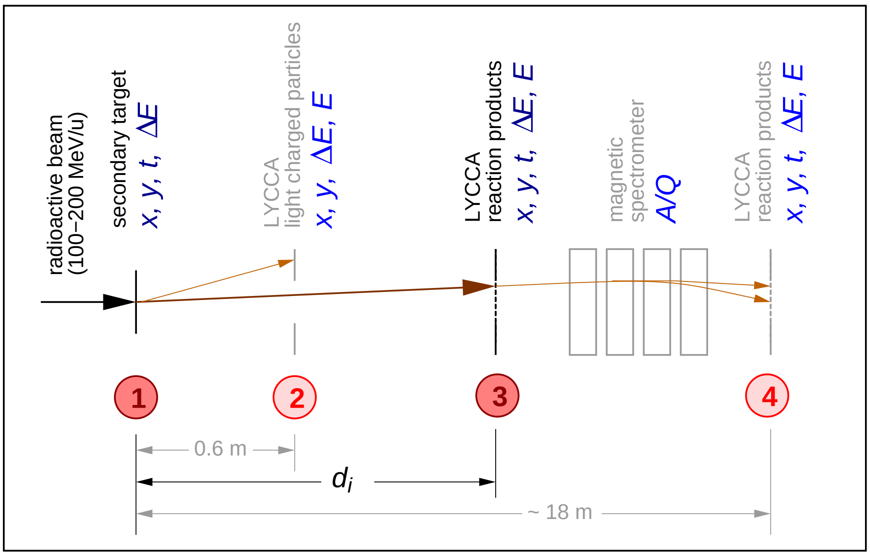

Figure 3: Schematic overview of the proposed LYCCA-0 (dark colors) and LYCCA (light colors added) set-ups. The distance d_i amounts to $d_1 \sim 3.4$ m for LYCCA-0 and $d_2 \sim 4$ m or $d_3 \sim 9$ m, respectively, for LYCCA (cf. Fig. 1).

In the following, the detector arrangements to be used for initial parasitic FRS in-beam tests and the 'LYCCA-0 + RISING' (PreSPEC) set-up are going to be detailed. The basic components and techniques are well established by means of previous experimental efforts and their functioning is underpinned by extensive LYCCA simulations presented briefly in Sec. 5 and the corresponding publication[9]. A 3D-GEANT4 sketch of LYCCA-0 is also included in Sec. 5. The LYCCA-0 elements comprising DSSSD and CsI detectors will turn into LYCCA elements, likewise the LYCCA-0 target chamber, which will already now be designed for future use at HISPEC. It is also clear from the simulations that optimal mass resolution requires optimal timing measurements. As a consequence the ToF solution fully based on polycrystalline diamond detectors forms the optimal but also most expensive solution. Therefore, LYCCA-0 and an early implementation of LYCCA foresee the (backup) use of a large-area plastic scintillator in front of the LYCCA modules. The scintillator is readout with fast photomultipliers processed further with integrated fast timing electronics (see Sec. 2.5.4).

[9]M.J. Taylor *et al.*, Nucl. Instr. Meth, to be submitted.

2.1 Position 1: secondary target

For LYCCA experiments, two major classes are considered: secondary fragmentation and relativistic Coulomb excitation. In both cases, position and timing information of the reaction products produced in the secondary target must be recorded. Note that also any detector placed there acts as a target.

For secondary fragmentation reactions, a typical $\sim$ 500 mg/cm^2 thick ^{9}Be fragmentation target will be followed by a 0.31 mm ($\simeq$ 70 mg/cm^2 silicon) DSSSD detector of the type described in Sec. 2.5.1 and a set of four $\sim$ 8.4 cm^2 CVD diamond detectors ($\simeq$ 50 mg/cm^2 carbon) detailed in Sec. 2.5.3. For relativistic Coulomb excitation experiments a $\sim$ 400 mg/cm^2 thick gold foil will be followed by the same detector sequence.

The DSSSD detector has a physical pixel size of 1.8×1.8 mm^2. Since the energy loss signals are huge (cf. Table 1), not only the directly hit strips but also neighbouring strips are going to process signals, and their relative heights further improve the position resolution (cf. AIDA[10] Technical Specification). The active area of the 0.31 mm thick DSSSD is 58×58 mm^2, 32 strips on each side, being neccessary and sufficient for existing and envisaged secondary beam spots of the FRS and Super-FRS, respectively.

The active area of the polycrytalline CVD diamond detector arrangement has a similar size, namely four elements of 29×29 mm^2. Their thickness will be on the order of 0.25 mm in order not to compromise energy loss and straggeling of the passing particles vs. capacity and mechanical stability. Its purpose is *exclusively* to provide an *optimal timing signal* for the start of the ToF measurement. Energy and position information is *no issue* for this detector. For reasons of cost per cm^2, mechanical stress, signal propagating times within the detectors, but at the same time minimising dead areas, an arrangement of four detectors sized 29×29 mm^2 is best for this position. For reasons of radiation hardness and count rate capabilitites, it is also clear that the timing at the target must be based on polycrystalline detectors.

Further electrical segmentation of each 29×29 mm^2 wafer is an option when moving from LYCCA-0 to LYCCA. Alternatively, more generic tracking detectors presently being developed for the Super-FRS might find their use at the HISPEC secondary target position in the future.

The 64 signals for the DSSSD as well as the 4 signals for the CVD diamond detector will be taken out of vacuum via two 32-channel, 50-Ohm adapted printed circuit boards (DSSSD) and one 4-channel, 50-Ohm adapted printed circuit board (diamond). For LYCCA-0, these feedthroughs have to be worked into the bottom flange of the existing RISING target cross. A permanent or movable (in-beam and out-of-beam) mechanics is being developed at the University of Cologne and GSI to hold the two detectors on this bottom flange (see also Sec. 2.5.1). For 'LYCCA + HISPEC', corresponding feedthrough arrangements have to be taken care of in the design of the future HISPEC target chamber.

[10]AIDA: Advanced Implantation Detector Array for DESPEC; T. Davison@ed.ac.uk

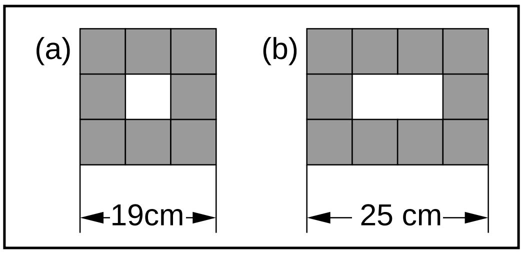

Figure 4: Two possible arrangements of the LYCCA light charged particle array. Each grey square represents a 62.5×62.5 mm^2 LYCCA-lcp module.

2.2 Position 2: light charged particle array

The light charged particle array is considered to be an upgrade of the core 'LYCCA + HISPEC' set-up beyond the year 2014. Its modules comprise the same DSSSD detectors as the fragment array (see next paragraph) but thicker CsI elements to stop up to 100-150 MeV protons. Figure 4 illustrates possible arrangements, which are positioned some 60 cm downstream from the secondary target. Arrangement (a) covers angles between $\sim 3°$ and $\sim 10°$. Mechanically, they will easily fit into the planned $\sim$ 40 cm wide beam pipe, i.e., only some simple mechanical support and vacuum feedthrough arrangements will have to be added, besides a rather modest number of by then ($\geq$ 2013) ASIC-based electronics channels.

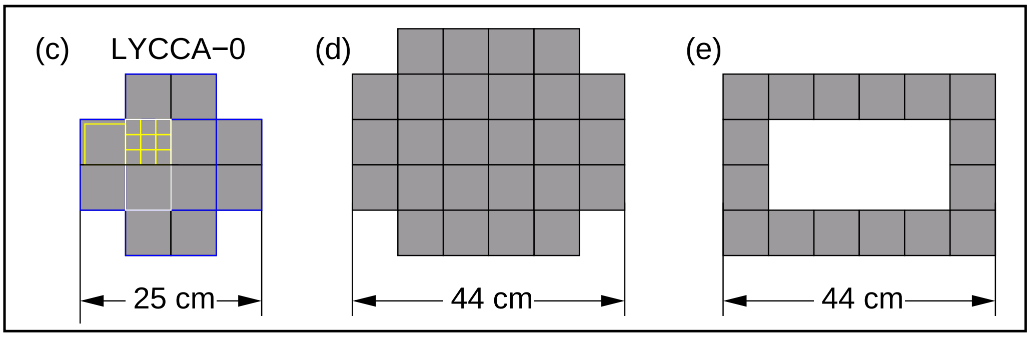

Figure 5: The LYCCA-0 array (c) and two possible arrangements of the LYCCA array (d),(e). Each grey square represents a 62.5×62.5 mm^2 LYCCA module. For (c), the white frame indicates anticipated additional CVD diamond timing, while the blue frames imitates the large-area plastic scintillator for the ToF stop measurement. The yellow squares exemplify the new CsI elements for the four central LYCCA modules and the existing CATE CsI elements for the eight outer LYCCA-0 modules.

2.3 Position 3: fragment array

The LYCCA fragment array should comprise a given number of ΔE–E modules (up to 30) with a 'timing wall' in front comprising either one large-area plastic scintillator or, ultimately, nine 19×19 mm^2 diamond wafers per module for the ToF stop signal. The configuration of the LYCCA-0 array and two possible configurations for 'LYCCA + HISPEC' are sketched in Fig. 5. Arrangement (e) implies a placement at the $d_2 \sim 4.0$ m position (called '1' in Fig. 1) and allows heavy fragments on central trajectories to enter the magnetic spectrometer. Arrangement (d) implies a wall-type set-up, similar to the one to be used at for LYCCA-0. The latter covers angles up to some 2.2° when placed at $d_1 \sim 3.4$ m) downstream the secondary target in the S4 area of the FRS, which is similar to the above mentioned closest position at HISPEC at 4.0 m.

The ΔE detectors are 0.31 mm thick, square-shaped DSSSD with an active area of 58×58 mm^2, and having 32 strips on each side. They are identical to the ones discussed for the target area but mounted on new PCB frames to avoid dead space. For more details see Sec. 2.5.1.

The E detectors for the four central LYCCA-0 (and all future LYCCA) modules are square CsI detectors, nine of which fit behind one ΔE DSSSD: Their active size is 19.0×19.0 mm^2 with a wrapping of 0.25 mm (2-3 layers) VM2000/ESR foil to improve surface light reflection properties. They cover a total size of 58.5×58.5 mm^2. Their depths is 13 mm plus a 7 mm pyramid, within which the outer dimensions are reduced to 10×10 mm^2. They are readout by 10.5×11.5 mm^2 sized photodiodes. For more details see Sec. 2.5.2. Note that for high-energy experiments in light mass regimes thicker ($\sim$ 30+7 mm) CsI detectors are needed. These thicker CsI elements are identical to those foreseen for the light-charged particle array (see above).

Corresponding in size (19.0×19.0 mm^2), nine polycrystalline CVD diamond detectors form the optimum ToF stop signal for each LYCCA module. This LYCCA ToF stop 'wall' will be implemented gradually until 2014 upon availability of CVD diamond detectors. For both LYCCA-0 and an early implementation of 'LYCCA + HISPEC' thin (1 mm and 2 mm) large-area fast plastic scintillators are available. Fast photomultipliers are connected to the scintillators, the signals of which are processed further with the same (existing) integrated fast timing electronics foreseen for the CVD diamond detectors.

For the implementation of LYCCA-0 there is the need for an extension pipe toward larger distances in the FRS S4 area as well as the construction of the LYCCA vacuum chamber. Schemes and CAD drawings are provided in Sec. 4 of this document. The pieces will be built at either the workshop of the University of Cologne (chamber) or GSI (extension pipe). The dimensions of the chamber are such that it will be possible to continue to use it for LYCCA. Special pieces to connect the chamber to the future Super-FRS/HISPEC beamline are simple and will be produced once the future HISPEC beamline layout and dimension is fixed.

For LYCCA-0 there are a total of 256 signals from the central four DSSSD (single-strip readout) plus 128 signals from the outer eight DSSSD (quadruple-strip readout). Alike the target position, these will be be taken out of the vacuum via 32-channel, 50-Ω adapted printed circuit boards (12×) preferably through the top section of the LYCCA chamber. There are a total of $4 \times 9 + 8 \times 1 = 44$ CsI signals. Four PCB vacuum feedthroughs for

16 signals each are foreseen. For LYCCA-0 there are a maximum total of $4 \times 9 = 36$ CVD diamond signals to be handled. Three 50-Ω adapted PCB vacuum feedthroughs for up to 16 signals each are foreseen. There is ample of space around the LYCCA chamber to add more feedthrough capacity when moving from the LYCCA-0 to the 'LYCCA + HISPEC' phase. The fast plastic scintillator and the associated photomultipliers are part of the extension pipe and situated some 30 cm upstream of the LYCCA modules.

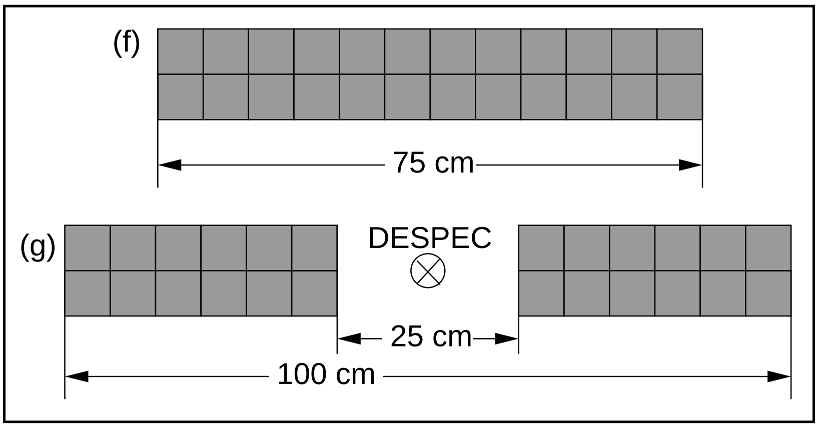

Figure 6: Two possible arrangements of the LYCCA array in the focal plane of the magnetic spectrometer. In version (g) the residues on central trajectories can be implanted in DESPEC for recoil decay tagging experiments.

2.4 Position 4: fragment array behind the magnetic spectrometer

The LYCCA detector modules will be identical to those described in the previous paragraph. Possible combinations of the flexible LYCCA modules are illustrated in Fig. 6. The corresponding final HISPEC/DESPEC arrangements depends on the design of the magnetic spectrometer and the subsequent energy buncher, which both do not have a final design at the time of writing this TDR.

Recent (April 2008) cross-check with the people presently in charge of the design of the magnetic spectrometer (Ch. Nocifori, H. Geissel) revealed that the physical size of the focal plane in x and y for LYCCA to cover is similar if not identical to the position 3 at the entrance of the magnetic spectrometer. The combination of the magnetic spectrometer with LYCCA ToF, ΔE, and E measurements and the possible of use of other tracking detectors is going to allow for A and Z discrimination to to mass $A = 250$.

Nevertheless, even in case the design of the magnetic spectrometer would be subject to further changes, LYCCA is designed such that the only requirement for the different calorimeter version in Fig. 6(f) and the recoil-decay-tagging option in Fig. 6(g) would be an additional, simple, rectangular vacuum chamber with vacuum feedthroughs identical to those of the presently planned LYCCA chamber for use at the FRS and positions 1 and 2 of Fig. 1. Taking a reasonable time line of the whole NuSTAR project into account, there is ample time for a construction of a possibly necessary second vacuum chamber, including solving possible monetary issues.

2.5 LYCCA detector characteristics

2.5.1 DSSSD

Si-wafer:
The DSSSD wafers are produced at RADCON Ltd., Zelenograd, Russia, and are bonded on custom made printed circuit frames at Lund. The typical characteristics of a DSSSD are (according to a sample data sheet) summarized in Table 2. The wafers are the same for the tracking detector at the secondary target position and the LYCCA fragment array. For the LYCCA-lcp array somewhat thicker wafers will be used; $\sim$ 520 μm. Two detectors for the target area exist, six LYCCA wafers of $\sim$ 310 μm are delivered and to be bonded at Lund, six wafers are on order and to be delivered during summer 2008. These are financed through Swedish Pre-FAIR grants. An additional eight wafers will be ordered later in 2008, financed through RISING running costs. These 22 wafers cover LYCCA-0 demands including spares. Note that the S-FAIR (S='Swedish') investment money concerning the remaining wafers and spares for LYCCA awaits (preliminary) approval of the present TDR.

Table 2: Overview of DSSSD wafer characteristics.

Chip dimension:	$(60.0 \pm 0.2) \times (60.0 \pm 0.2)$ mm^2.
Active area:	58.0×58.0 mm^2.
Number of strips:	32×32.
Interstrip distance:	75 μm.
Thickness:	(303 ± 3) μm.
Dead layers:	junction 0.48 μm, ohmic (0.55 ± 0.10) μm.
Full depletion voltage:	typical 40 V.
Operating voltage :	50 V.
Total capacity:	1060 pF.
Resistivity:	6.3 kΩ·cm.
Leakage current:	10–15 nA per strip.

Printed circuit boards:
Drawings of the printed circuit boards holding the DSSSD wafers at the secondary target position and inside a LYCCA module are shown in Fig. 7(a) and (b), respectively. The connectors on the board (a) are KEL 8831E-068-170L[11] or, being identical, 3M Robinson Nugent P50E-068P1-SR1-TG (plugs). The respective mating connectors are, for example, KEL 8801-068-170L (boardmount receptacle) and KEL 8825E-068-175S or 3M Robinson Nugent P25E-068S-TG (wire mount receptacles).
The LYCCA board in Fig. 7(b) will be connected to to signal-transport PCBs ('T1' and 'T2') by two rows of BLX-1-056-40G female headers and SLX-1-053-30G male headers from

[11] `http://www.kel.jp/english/e-pdf/C51-58_8822E.pdf`

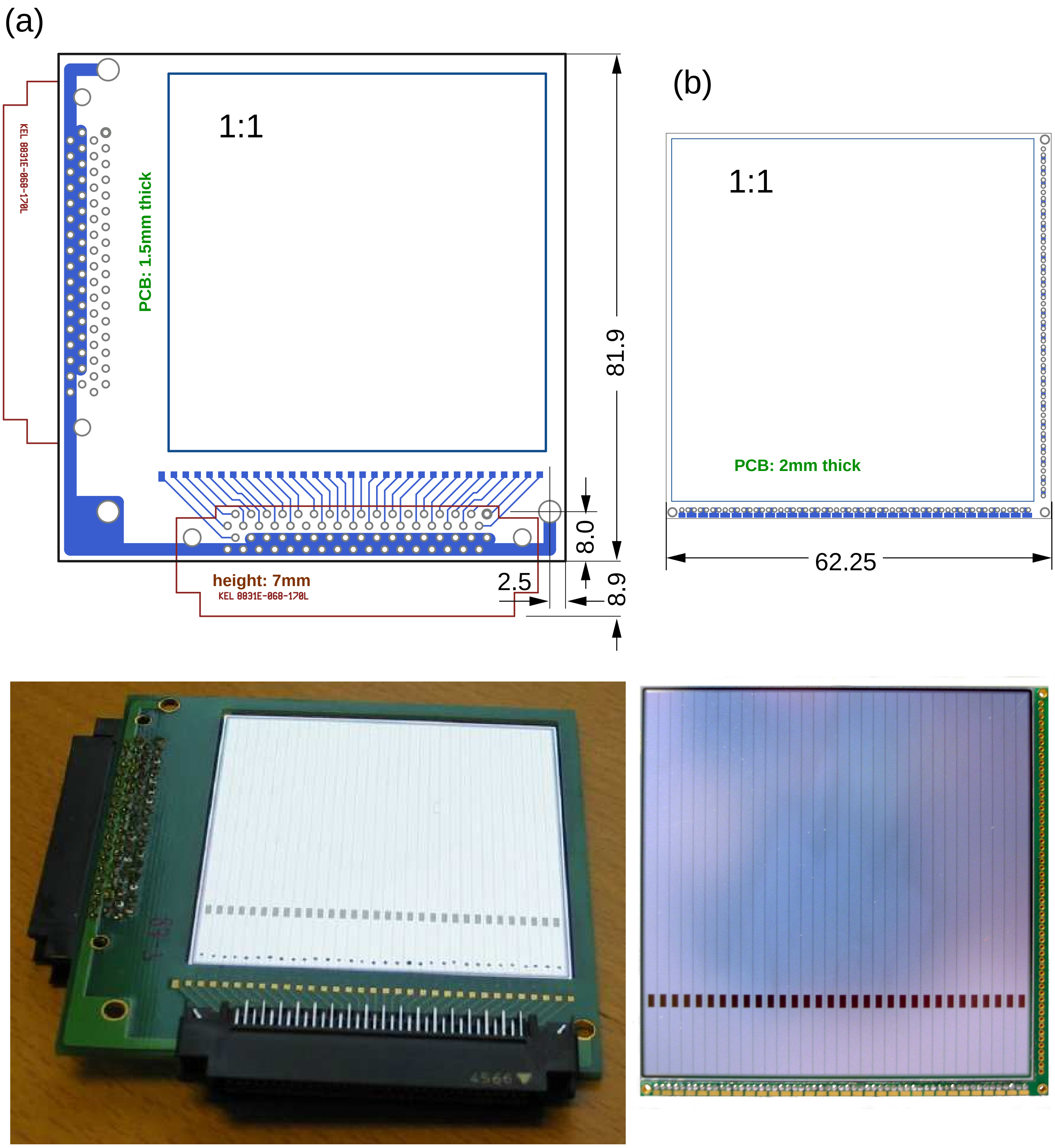

Figure 7: Printed circuit board layout and picture of the DSSSD tracking detector at the secondary target position (left hand side), and the PCB layout for a LYCCA DSSSD (right hand side). The silicon wafers are the same in both cases. For (a), the mechanical mounting holes are positioned at 2.5 mm and 8.0 mm from the outer border of the PCB, respectively. They have a diameter of 3 mm. PCB (b) will be connected to downstream PCBs (see Fig. 8) keeping the overall outer dimensions of a LYCCA module at 62.5×62.5 mm^2 (allowing for 0.25 mm additional space between modules).

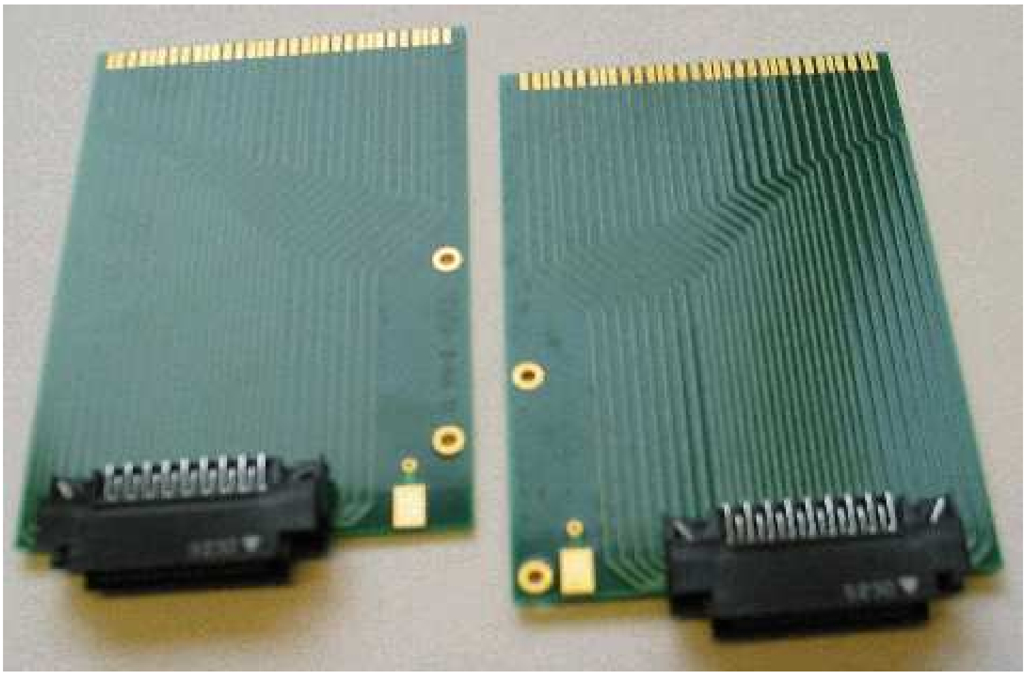

Figure 8: Picture of the signal-transport PCBs ‘T1’ and ‘T2’ guiding the 32 plus 32 signals from the DSSSD into two KEL 8831E-034-170L connectors. They will be glued at a 90° angle.

the German company fischer elektronik[12]. The connectors have a 1 mm pitch and each row has 58 pins, i.e., most of the strips are connected by 2 pins, and a few by only one pin.
The signal-transport PCBs are shown in Fig. 8. Together with the DSSSD-PCB in Fig. 7 and a holding/mounting rod they form the DSSSD part of a LYCCA module. At the back end of ‘T1’ and ‘T2’ the signals exit via KEL 8831E-034-170L (P50E-034P1-SR1-TG) connector plugs. In case of using the DSSSD for dedicated timing purposes, either ‘T1’ or ‘T2’ has to be re-designed for 50-Ω adaption.

2.5.2 CsI

In the class of non-hydroscopic inorganic scintillators CsI is still the best as far as charged-particle energy resolution is concerned. Recent studies of characteristics and CsI-photodiode (PD) combinations have been done, for example, at MSU[13] or within the related NuSTAR-R3B/EXL[14] projects. The energy resolution of CsI detectors is directly coupled to the efficiency of light collection and the uniformity of light collection over the active volume of the detector. The former has to be optimized during the preparation of a CsI detector element. Depending on the size of the effect, the latter can be corrected for by using the position information of the incoming ion via the preceding DSSSD detector. There is also a variation of the light output as a function of temperature. Eventually, a constant temperature

[12] `http://www.fischerelektronik.de`
[13] M.-J. van Goethen *et al.*, Nucl. Instr. Meth. A 526, 455 (2004).
[14] EXL: EXotic nuclei ... studied in the NESR storage ring;
The EXL Si-Si-CsI(Tl)/PD recoil system, V. Avdeichikov, B. Jakobsson, and the CCG group

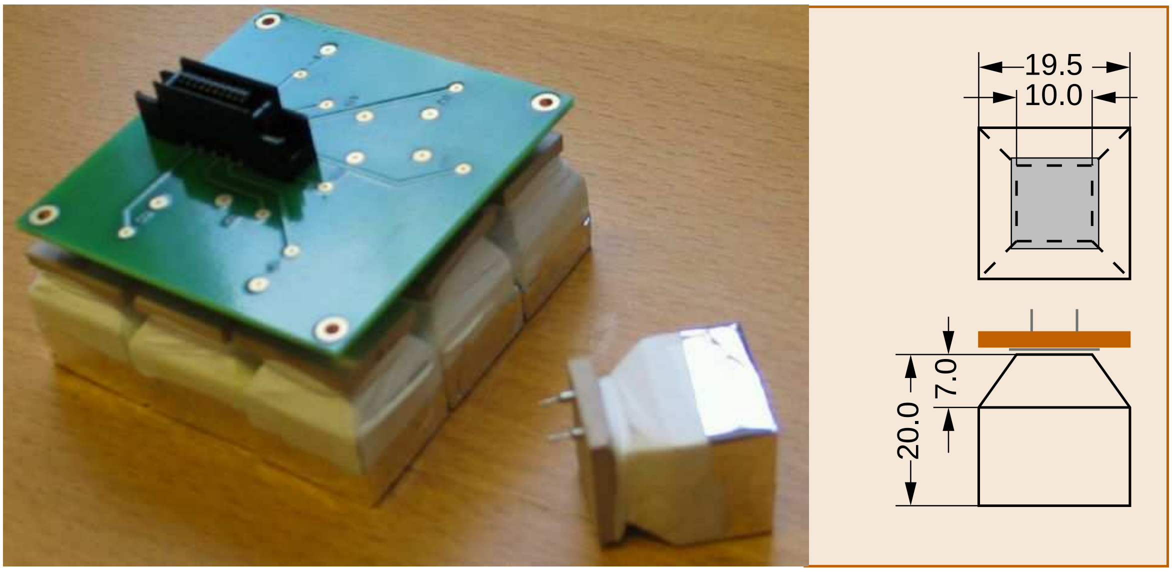

Figure 9: Picture of the first batch of LYCCA-CsI detector elements. It shows a package of 3×3 backed by the PCB. When mounted, the connection between the pins of the photodiodes and the PCB will be done with very short, thin shielded coax-cables. On the right hand side is a technical sketch with the most important numbers. The placement of the photodiode is indicated in grey.

has to be induced into the target chamber (for example, 20° C), depending on the in-beam performance of LYCCA-0.

40 CsI test samples have been ordered and delivered. The CsI(Tl) crystals originate from Kharkov, Ukraina. They have a 19.0 × 19.0 mm^2 frontface and a depth of 13 mm. In the course of a pyramid of additional 7 mm depth, the face is reduced to 10.0 × 10.0 mm^2 (cf. Fig. 9). The crystals are wrapped in typically three layers of teflon tape, or more recently VM2000 foil, summing up to about 0.25 mm. Thus one CsI detector element is effectively 19.5 × 19.5 mm^2 in size.

The photodiodes are 10.5 × 11.5 mm^2 in size, produced by RADCON, and glued directly onto the light guide of the crystal by means of EPOXY TECHNOLOGY EPO-TEC 301 optical epoxy. Figure 9 includes a picture of one element. In terms of noise reduction it is better to compromise some light efficiency towards the smaller photodiode rather than using a 4× larger photodiode with larger capacitance. Bench tests with these elements have been very satisfying and are illustrated in Fig. 10.
In 2007, first in-beam tests were performed with 180 MeV protons at TSL Uppsala. The protons passed through a LYCCA target DSSSD detector and stopped in long CsI(Tl) crystals (180mm, CALIFA-R3B prototypes). Both the CsI material and the photodiodes were

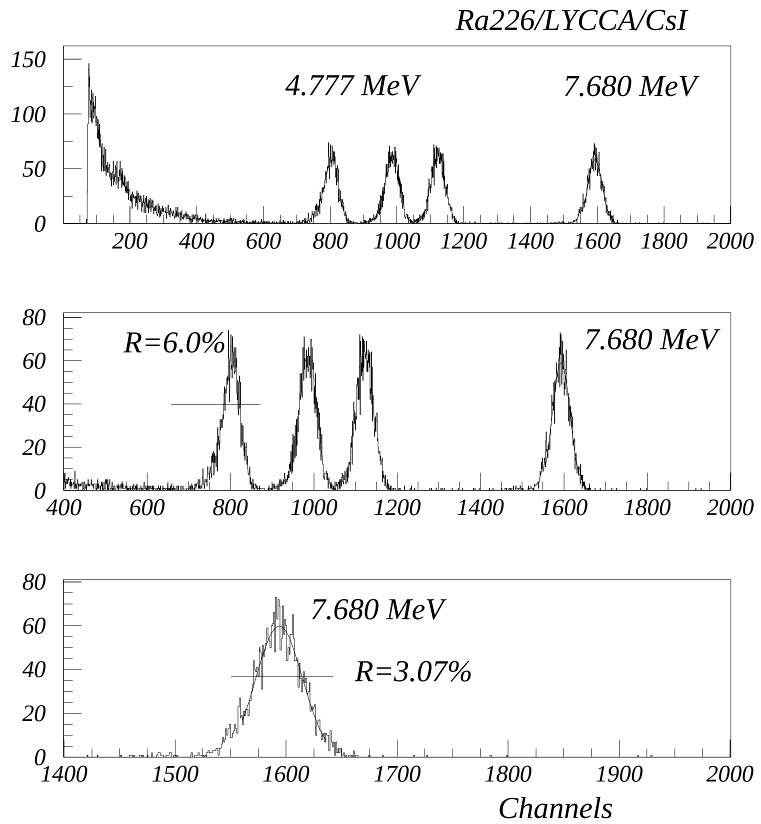

Figure 10: Energy spectra of a ^{226}Ra α source measured by a LYCCA-0 CsI/PD prototype. Energy resolutions are indicated for 4.777 MeV and 7.680 MeV α lines.

identical to the LYCCA modules. Fig. 11 shows the energy spectrum of one CsI, providing an energy resolution in the peak of better than 0.6% for protons. The background, which is due to elastic and inelastic scattering of the protons, will be significantly less for heavy ions, and the light collection and thus the energy resolution will be even better for the smaller LYCCA CsI(Tl) detectors. This proves the feasibility of an upper limit of 0.5% energy resolution for the LYCCA CsI system used in the simulations.

For 'LYCCA-0 + RISING' the eight outer DSSSD (cf. Fig. 5(c)) will be backed by the former CATE CsI detectors. These are 54×54 mm^2 in size and either 10 mm or 30 mm thick. See R. Lozeva *et al.*, Nucl. Instr. Meth. A562, 298 (2006) for more details. The CATE CsI detectors in conjunction with the 40 new CsI elements cover the needs of LYCCA-0. These 40 CsI crystals, photodiodes, and preamplifiers were financed through Swedish Pre-FAIR grants. Further Swedish investment on CsI requires the (preliminary) approval of this TDR.

Figure 9 includes also the PCB to be used with the CsI elements. The signals are processed through short ($\sim$ 10–20 mm) shielded cables (Filotex 50 Ω VMTX miniature PTFE coaxial cables, Farnell 157284) from the photodiode pins to the PCB. Here, they connect via a KEL 8830E-020-170S (P50E-020P1-S1-TG) plug. The PCB is 58×58 mm^2 in size, 2 mm thick, and the centers of the 2 mm mounting holes in the four corners are 3 mm away from each of the borders. The CsI block of nine elements enters the LYCCA module about 10 mm behind the DSSSD wafer.

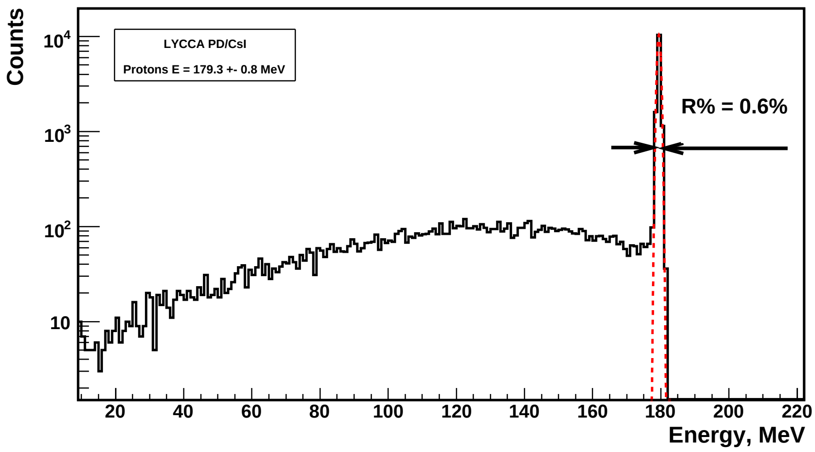

Figure 11: Energy deposit of 180 MeV protons in 180mm long, CALIFA-R3B prototype CsI crystals.

2.5.3 Polycrystalline CVD diamond

As the simulations in Sec. 5 show, the time-of-flight (ToF) measurements mandate that the timing detectors have sub-100 ps timing resolution (FWHM) in order to achieve the required performance for mass identification. Indeed, since the energy resolution of the CsI detectors can approach < 0.5 %, then a timing resolution of about 50 ps (FWHM) is required to ensure that the uncertainties associated with total energy and with ToF are comparable when determining mass from energy and time. To date such a resolution has only been achieved with chemical vapour deposition (CVD) diamond detectors. Both single-crystal (sCVD) and polycrystalline (pCVD) diamond detectors have been used over the last decade in high-energy physics [15] and, more recently and in a developmental way, in nuclear physics [16]. Both sCVD and pCVD diamond have excellent timing properties: so far timing resolution of a few tens of picoseconds has been achieved — including electronic contributions. For example, $\sigma = 28$ ps was achieved by Pomorski *et al.* using 2 GeV/A ^{27}Al ions for timing between two diamond detectors. Both sCVD and pCVD crystals showed the same result [17]. Stolz *et al.* obtained $\sigma = 21$ ps (FWHM = 50 ps) between two heteroepitaxial diamond crystals. sCVD diamond has an energy resolution approaching that of silicon, but can only be grown presently to crystal sizes of about 1 cm in diameter. pCVD material can be grown to much larger wafers, but charge-trapping at the crystal boundaries destroys the energy resolution.

As we do not require an energy measurement from the diamond, then the pCVD diamond presents an excellent solution. In other words: the pCVD diamond detectors planned for LYCCA aim solely at optimum ToF measurements. In addition, pCVD diamond has the advantages of being robust, radiation hard and electrically simple (a diamond detector behaves as a 'pure' capacitor).

[15]M. Pomorski *et al.*, Phys. Stat. Sol. 202, 2199 (2005).
[16]A. Stolz *et al.*, Diam. Rel. Mat. 15, 807 (2006).
[17]M.Pomorski *et al.*, Phys. Stat. Sol. 203, 3152 (2006).

The implementation of pCVD diamond on the rather large scale required for LYCCA (6×6 cm^2 of diamond for each module) has not been attempted previously, and some development issues are presented, which we are going to address starting 2008. The principal issues are:

- Wafer size; Fabricated detectors have not yet been made of the size required for the application here.
- Manufacturing; Fabricated CVD diamond detectors have not yet been produced commercially, although the technology exists and and some companies (for example, UK-based Diamond Detectors Ltd) have been established for this purpose.
- Capacitance issues; So far, for fast timing applications, only small detector areas have been used. As the timing resolution is expected to worsen proportionally to $\frac{dV_C}{dt}$ where V_C is the 50 Ω output pulse, the time-constant RC should be as short as possible. Large-area detectors will need to be electrically segmented to reduce capacitance, and the degree of segmentation needs to be established.
- Fast electronics; Dedicated broadband current pre-amplifiers are essential for this application. These are available amongst others via GSI-based high-energy nuclear physics projects (FOPI, HADES, CBM), although a specific method for digitizing the output for a large number of channels may need to be developed.

A collaboration has been developed between University of York, Surrey University and Diamond Detectors Ltd to undertake the remaining R&D on this project using the dedicated detector-fabrication laboratory facilities at Surrey. Considerable expertise exists at Surrey in fabrication of diamond detectors. Initially, pCVD CVD wafers (200 and 300 μm thick) will be purchased by York from Element6 (through Diamond Detectors Ltd). These wafers will be characterised at Surrey to assess their suitability for fast-timing measurements. Initially, sufficient diamond is required to cover two full LYCCA modules and the target area (see Sec. 2.1). The target will consist of four wafers, 29×29 mm^2 in size, and there will be nine 19×19 mm^2 wafers for each LYCCA module. The quality and consistency of the material (for example, crystallite size etc.) will be assessed on both the polished growth and nucleation sides of the wafer. Fabrication of the detectors from these wafers will be carried out at Surrey using the dedicated detector clean rooms. The photolithography and metal deposition processes and contact geometries will be optimised to achieve best detector sensitivity and timing performance. Initial source tests will be performed at Surrey, followed by in-beam testing (at the Birmingham cyclotron, using 30-40 MeV 3He/4He, or at the Tandem accelerator of the University of Cologne). This R&D programme is already underway, and it is anticipated to have sufficient diamond detectors in place for testing in the commissioning experiment of the LYCCA-0 phase in mid-2009. There is a related R&D programme ongoing at the TU Munich in the framework of the NuSTAR-R3B experiment, also using already pCVD diamond wafers from Diamond Detectors Ltd. Obviously, there will be intense consultations between the involved institutes.
In the LYCCA-0 phase, the diamond solution for the fast timing will be compared with and backed up by a more conservative but thus established method by means of a large-area plastic scintillator readout by a number of dedicated photomultipliers.

Assuming the CVD diamond is the ultimate ToF solution, the UK bid for the diamond detectors is based on wafers of 300 μm thickness of 19×19 mm^2 active area - nine of which form a timing detector in front of the DSSSD. The size is matched to that of the CsI to avoid dead space. We further assume that each detector is two-fold segmented, to reduce capacitance.

2.5.4 Large-area fast plastic scintillator

The large-area fast plastic scintillator acts as time-of-flight stop signal in the LYCCA-0 phase and serves as a potential backup for an early LYCCA implementation at HISPEC. It is a 1 mm thick, 25 cm diameter circular "active area" consisting of BC-420 scintillar material. On the test stand, the signals are induced by means of a UV-laser.

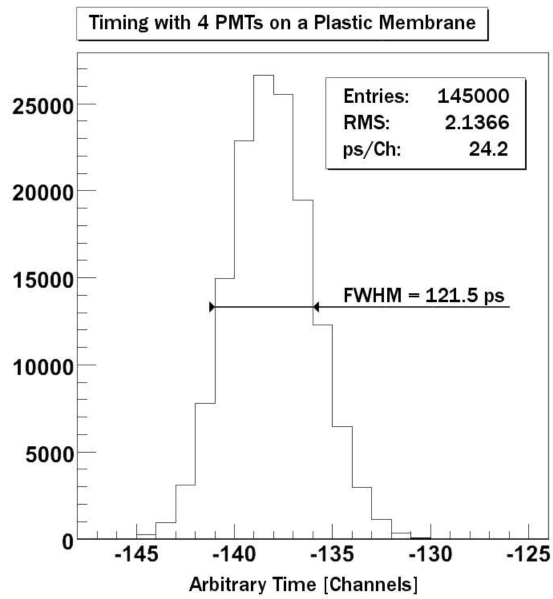

Figure 12: Sample spectrum of the timing response of the basic LYCCA-0 large-area scintillator evaluated with four photomultiplier tubes.

At the present (spring 2008) testing stage, four large photomultiplier tubes (PMTs) are attached to this BC-420 scintillator foil. The PMTs are Hamamatsu H2431-50, having 700 ps rise-time and 370 ps transit time spread. The signals are further processed by dedicated constant fraction discriminators type Phillips Scientific Model 715 and digitized by means of modern commercial CAEN 1290A VME TDCs providing a binning of only 25 ps per channel. Figure 12 shows a sample timing spectrum of these basic tests providing already a FWHM of about 120 ps, which contains both electronics contributions (some 55 ps) and detector system related contributions (some 110 ps). Using only two of the four scintillators, the latter contribution is found to increase by a factor of $\sqrt{2}$.
For the implemantation of LYCCA-0 it is therefore planned to add another four new, extra fast PMTs, i.e. the scintillator light is going to be evaluated by a total of eight PMTs.

This should (i) further reduce the nominal detector-related FWHM to some 80 ps and (ii) make this number more and more independent on position. The new PMTs are high-standard Hamamatsu R3809U-52 with as little as 150 ps rise-time and 25 ps transit time spread. Depending on financial capabilities, also the four existing PMTs may gradually be replaced by these. The second major improvement towards LYCCA-0 foresees the use of fast integrated timing electronics, namely the TACQUILA chip, which has been developed at GSI for multichannel ToF experiments demanding 'very high timing resolution' [18]. The additional time jitter induced by this chip can be regarded neglidgible against the detector-related FWHM, i.e. this improved scintillator based ToF stop arrangement is going to reach the basic goal of ≤ 100 ps timing.

It should be noted that there is an existing VME electronics scheme to readout the TACQUILA system also developed at GSI, which can be copied for very low cost. Similarly, the inclusion of the TACQUILA data structure into the GSI-MBS data acquisition has already been done. Both hardware and software are to be included in the scintillator test stand in spring 2008 by the Lund-GSI PhD student with GSI support from the Gamma-ray Spectroscopy Group.

Finally it should be stressed that the TACQUILA-based electronics are going to be used for diamond detector signal processing as well, i.e. both hardware and software is going to be at hand as soon as the first diamond detectors are delivered. In fact, diamond detectors have already been tested at the GSI detector laboratory using TACQUILA electronics.

2.5.5 Summary LYCCA-0 Detectors

The following table summarizes the status of the LYCCA-0 detector components and remaining investments towards an implementation of LYCCA-0 at RISING.

Table 3: Summary of LYCCA-0 detector equipment as of December 2007.

subdetector	stock	order	need	remaining cost	money source	status
DSSSD wafer target	2	—	—	—	Lund	ready
DSSSD target consumption	—	2	—	4 kEUR	RISING	ordered
DSSSD wafer LYCCA-0	6	6	—	12 kEUR	Lund	ready/ordered
DSSSD LYCCA-0 consumption	—	—	8	16 kEUR	RISING	ordered
CATE CsI elements '10mm'	9+	—	—	—	RISING	ready
CATE CsI elements '30mm'	9+	—	—	—	RISING	ready
LYCCA-0 CsI elements '10mm'	40	—	—	—	Lund	ready
CVD diamond target	—	—	4	8 kEUR	York	ordered
CVD diamond LYCCA-0	—	—	20	40 kEUR	York	ordered
Photomultiplier tubes	—	—	4	45 kEUR	Lund/GSI	pending

[18] TACQUILA: `http://www.gsi.de/onTEAM/grafik/1130845854/tacquila.pdf`

3 Electronics

The by far largest number of electronics channels is going to be related to the DSSSD detectors in the final LYCCA set-up. For example, the configuration in Fig. 5(d) comprises 2×896 strips. Adding the LYCCA-lcp array in Fig. 4(a), this would imply a total number of silicon electronics channels of 2304. This number is clearly excluding the use of 'classical' electronics schemes and calls for application specific integrated circuit(ASIC) developments. Luckily, the already funded AIDA project within DESPEC foresees such an ASIC development, and the respective projected chip with the two complete energy ranges (high-energy implantation and low-energy decay) can serve the DSSSD energy-loss measurements of both the LYCCA fragment array *and* the LYCCA light charged particle array. For more detailed specifications of the AIDA (and LYCCA) DSSSD chip we refer to the AIDA TDR.
The number of CsI electronics channels for the (maximum) LYCCA set-up indicated above is 324. This is still on the level to be handled conventionally. In itself, the low number does not justify a dedicated ASIC development either. Hence, the solution for LYCCA will either be off-shelf conventional electronics or using a proper ASIC chip, which may be developed in the framework of other NuSTAR branches — for example CALIFA, the R^3B calorimeter — or for upcoming SPIRAL-2 experimental set-ups. Conventional electronics for the order of 324 channels is already existing within the LYCCA collaboration, namely in form of preamplifiers, amplifiers, and ADCs as well as TDCs used for the LYCCA-0 DSSSD signal processing.
Independent of the type of time-of-flight detection system, i.e. for both CVD diamond and scintillator-PMT timing, the alerady existing GSI-based TACQUILA chips are going to be used, as explained in the previous section. Even these and their subsequent readout scheme is established to work at GSI.

Table 4: Summary of electronics channels for a prototype test, LYCCA-0, and LYCCA in the configuration described in the text. The latter is split in configuration A (scintillator stop timing) and configuration B (full diamond timing).

subdetector	test	**LYCCA-0**	LYCCA-A	LYCCA-B
energy/time target DSSSD	64	**64**	64	64
energy/time LYCCA DSSSD	96	**320**	1792	1792
energy/time LYCCA lcp DSSSD	—	—	—	512
energy/time LYCCA CsI	10	**44**	252	252
energy/time LYCCA lcp CsI	—	—	—	72
ToF timing target diamond	2	**4**	16	16
ToF timing LYCCA diamond	2	**18**	—	252
ToF timing scintillators	4	**8**	8	—

For the **near future**, i.e., the 'LYCCA-0 + RISING' set-up, an electronics scheme and pool based on commercial modules is being developed within the LYCCA collaboration. The necessary number of electronics channels are marked bold in Table 4 and are detailed in Table 5, together with the status of the different detector elements (as of April 2008):
In the following, the items indicated above and in Tables 4 and 5 will be detailed.

Table 5: Summary of LYCCA-0 electronics equipment as of April 2008. Note that major parts of the main electronics will only be available during the RISING campaigns.

subdetector	stock	order	need	remaining cost	money source	status
12 32-channel DSSSD preamps	—	12	—	8 kEUR	Cologne/Lund	prototype ready
24 16-channel shapers and time	24	—	(2)	(8 kEUR)	York[a]	ready
12 32-channel CAEN 775 TDC	12	—	—	—		ready
12 32-channel CAEN 785 ADC	12	—	—	—		ready
CATE CsI PD preamps	18+	—	—	—		ready
2 32-channel LYCCA CsI PD preamps	—	2	—	2 kEUR	Lund	prototype ready
6 8-channel CAEN 1724 S-ADC	3	3	—	12 kEUR	Lund	ordered
4 16-channel ToF TACQUILA	—	4	4	?	RISING	ordered
1 TACQUILA VME readout	—	1	1	?	Lund/GSI	ordered

[a] 6+6+12=24 16-channel Mesytec units (=384 channels) from Lund-Cologne-RISING
2 spare units missing, York.

3.1 Cabling in the vacuum and vacuum feedthrough

For easy maintanance, all electronics are going to be located outside the vacuum chamber, both for LYCCA-0 and LYCCA. The influence of some 20–40 cm long 50 Ω coaxial cables between the detector and respective current preamplifiers on timing properties of silicon or diamond detectors has been investigated by Dr. W. König, GSI, and found to be marginal. Hence, all cabling inside the chamber will be done with 50 Ω coaxial cables of the type Filotex 50 Ω VMTX miniature PTFE coaxial cables, Farnell 157284 (or similar). Secondly, all PCBs related to ToF measurements have to be 50 Ω adapted by means of simple but multilayer techniques, including the vacuum feedthrough PCBs.
Since only normal vacuum is required, standard techniques can be used to glue PCBs into small, custom made flanges, which in turn are screwed into the walls of the LYCCA chamber with O-ring seals (see Sec. 4 for drawings). Preamplifier boxes (LYCCA-0) or respective front-end cards (LYCCA, e.g., the ones holding the AIDA ASICs) will plug directly into these vacuum PCBs, which are potentially a subject of change when moving from conventional to ASIC electronics, while the LYCCA chamber as such will be kept. It should be stressed that there are no serious space restrictions at the beam-line positions of LYCCA-0 and LYCCA chambers, respectively.

3.2 DSSSD electronics

LYCCA-0:
The electronics workshop at the University of Cologne develops a state of the art multi-channel, charge sensitive, low noise, 32-channel preamplifier module dedicated to single- or double-sided multistrip silicon detector readout — CSP_07-(2.5 GeV). Each preamplifier has

a 2.5 GeV silicon deposited energy dynamic range with a sensitivity of 50 mV/200 MeV (+/-20%). Differential output provides high noise immunity on the level of $\sim$ 3.5 keV +0.5 keV/pF dependence on detector capacity. The precursor CSP_07-(200MeV) version was successfully tested in the detector laboratories and fulfills the specification requirements beyond expectations.
The CSP_07 output signals are processed further by the Mesytec multichannel shaping amplifier module STM-16+ (http://www.mesytec.com/silicon.htm) followed by several 32-channel CAEN V785 Peak Sensing ADC and CAEN V775 TDC (http://www.caen.it/nuclear/index.php). The main amplifier modules and the digitizers are existing within the collaboration. A PCB adaptor board (CSP_07 to 2$\times$ STM-16+) was developed at Cologne to provide direct compatibility between the CSP_07 output connector (32 differential channels) and two Mesytec STM 16+ amplifier input connectors (16 differential channels each). Two industry standard twisted pair cable assemblies (34 wires, 0.05") can be used for the connection.
LYCCA:
All silicon related signals of LYCCA will use the AIDA ASIC currently being developed in the UK. A cross check via Ian Lazarus, Daresbury Laboratory, ensured compatibility. See the AIDA TDR for more details on the ASIC chip.

3.3 CsI

LYCCA-0:
The photodiode signals are at present processed by charge sensitive preamplifiers developed at JINR/Dubna. The dynamic range is approximately 15 GeV energy deposited into CsI with a noise level of 5.5 keV at 36 pF PD capacitance. The preamplifier output signal is digitally recorded by the CAEN V1724 8 channel 14 bit module with up to 100MS/s Flash ADC Waveform Digitizer (http://www.caen.it/nuclear/products.php). The JINR/Dubna preamplifiers are going to be exchanged versus the above mentioned 32-channel preamplifier modules from the University of Cologne. The pulse-shape readout is both feasible in terms rate and more importantly wanted to account for possible scattering or nuclear reaction background.
LYCCA:
The CsI signal processing after the preamplification stage for LYCCA will be in principle the same as for LYCCA-0, i.e., via individual sampling ADC channels. Currently, a prototyping of a generic 8-channel 100 Mhz sampling ADC is being pursued at GSI, which shall serve NuSTAR with a generic and relatively cheap (< 50 EUR per channel) module compatible with the NuSTAR data aquisition. An alternative might be an ASIC for inorganic scintillators, which might be developed and financed in the frame of other, more complex NuSTAR or PANDA detector systems. A fully compatible and existing back-up solution are the 384 channels of DSSSD related electronics from the LYCCA-0 stage.

3.4 CVD diamond

To obtain the required time resolution, specialized electronics are required. The fast-timing characteristics of diamond have, to date, been investigated using Diamond Broadband Am-

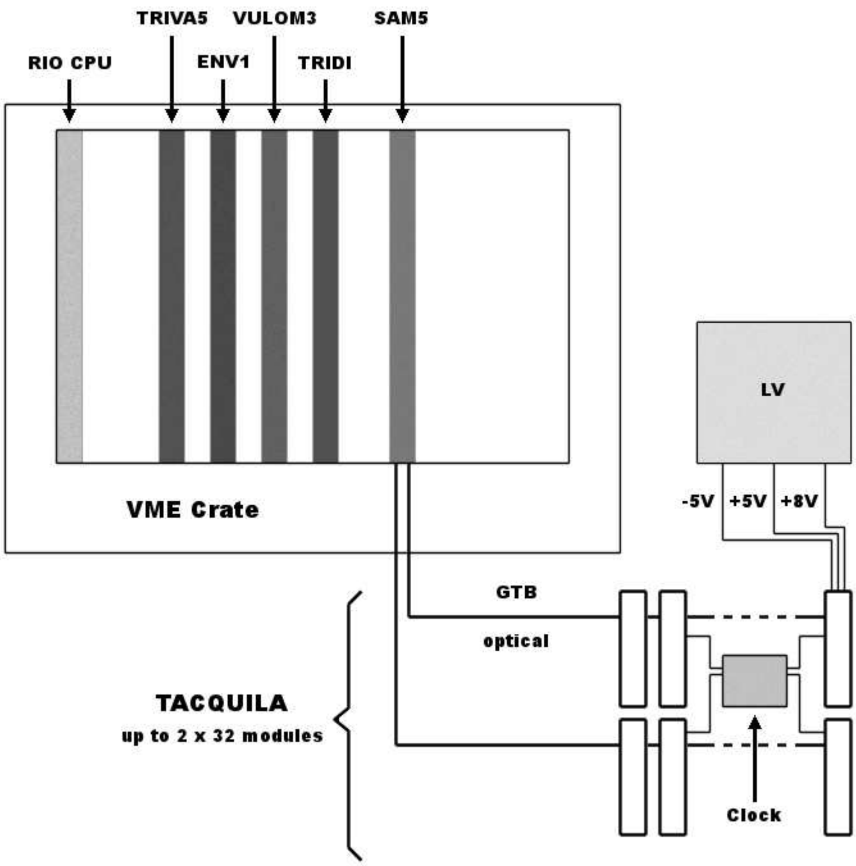

Figure 13: The VME based readout electronics for TACQUILA cards. Not mentioned in the text is the ENV1 16-channel ECL-NIM level converter and the low voltage power supply for the TACQUILA modules.

plifiers (DBA) – commercially available broadband current pre-amplifiers[19]. These are available in single- or eight-channel units. The current DBA (DBA-IV) is available commercially, but for the large number of channels required for instrumenting the full detector coverage (at least 500 channels) - a multi-channel fast digitization and readout scheme needs to be implemented.

The solution is based on the 4-channel front end electronics (FEE) cards developed at GSI for the FOPI project[20]. These custom-made cards essentially comprise broadband current preamplifiers and fast discriminators. This card, FEE1, is flexible in its application, with lemo input and output, and control of both gain and threshold via potentiometers. This solution has already been shown to be well suited to our needs. Using a 1-GeV Ta beam and a pCVD diamond detector, a timing resolution of $\sigma \leq 28$ ps was achieved using the 4-channel card. The proposal (the basis of the bid for UK funding) is that this commercially-available 4-channel unit is used and a dedicated digitisation/readout card (similar to that used for the Si ASICS for the DSSSDs) is designed on which a number of these 4-channel units (probably four) would be housed. These cards would use the TAC chips on which the TACQUILA

[19]P. Moritz *et al.*, Diam. Rel. Mat. 10, 1765 (2001).
[20]M.Ciobanu *et al.* IEEE Trans. Nucl. Sci. 54, 1201 (2007).

cards are based. There is considerable expertise at Daresbury and RAL (UK) in this area, and the synergy with the development for the FEE/readout cards for the DSSSD ASICs is welcome.
The above presented solution requires some development, for which we have requested funding for manpower and equipment. A back-up solution, requiring considerably less development, but with consequences in terms of flexibility, exists by using the fixed-gain 16-channel version of the same card (FEE5) designed specifically for the 16-channels of the RPCs for FOPI. These cards are designed to be read out by the existing TACQUILA3 digitization and readout cards - which houses a TAC chip, 12-bit ADC and readout control. The TACQUILA board provides a 10 ps RMS time resolution for each of its 16 channels, while the time resolution between two channels on two seperate cards is approximately 20 ps RMS. A 40 MHz clock provides the TACQUILA cards with a time reference for synchronisation. In this case, the TACQUILA system would be used for both pCVD diamond timing and the fast plastic scintillator readout (see below).

3.5 Fast scintillators

The read-out of the PMTs signals from the fast-scintillator ToF measurement is processed using the TACQUILA system – as with the back-up solution for the pCVD diamond detectors. The number of TACQUILA channels required, therefore, is not fixed, although a large number of channels can be dealt with in a very compact way - see an example scheme summarized in Fig. 13. Up to two times 32 chained TACQUILA cards (1024 channels) can be read out by one VME SAM5 module via optic GTB cables. Here the SAM5 module acts as a GTB readout and data processing card. A TRIVA5 module is responsible for readout control and produces a dead-time signal to avoid multiple gate generation. A VULOM3 universal logic module takes care of the dead-time locking and trigger prioritisation, while a TRIDI module gives the accepted trigger to the SAM5 module.
The cost of the basic VME readout system for later-on up to 1024 TACQUILA channels, including CPU, VME crate and all above mentioned electronics modules, is approximately 20 kEuro. One complete 16 channel TACQUILA card with add-ons costs around 1500 Euro a piece. Hence, adding more channels to the system during both the R&D phase and the LYCCA implementation phase only generates the cost of additional TACQUILA cards, as all readout electronics already is in place.

4 Design Concept and Mechanics

The mechanics design for LYCCA is led by the mechanics workshop at the Institut für Kernphysik, Universität zu Köln. It is performed within the 3D-CAD system CATIA-5, which is also the present standard CAD system used at GSI. All figures of this section are derived from CATIA-5 design files.
The design of the LYCCA detector chamber will provide the flexibility of various LYCCA detector configurations. Already the LYCCA-0 assembly with a smaller subset of detectors will be housed in the LYCCA chamber. The foreseen mechanical construction will provide full compatibility with the upgraded final full LYCCA setup. Ones defined, only rather trivial coupling flanges to the Super-FRS and HISPEC-DESPEC vacuum pipes are going to be necessary in the future. One should also note that the chamber can be mounted in both the standard calorimeter position of HISPEC and the position in the focal plane of the currently projected spectrometer.

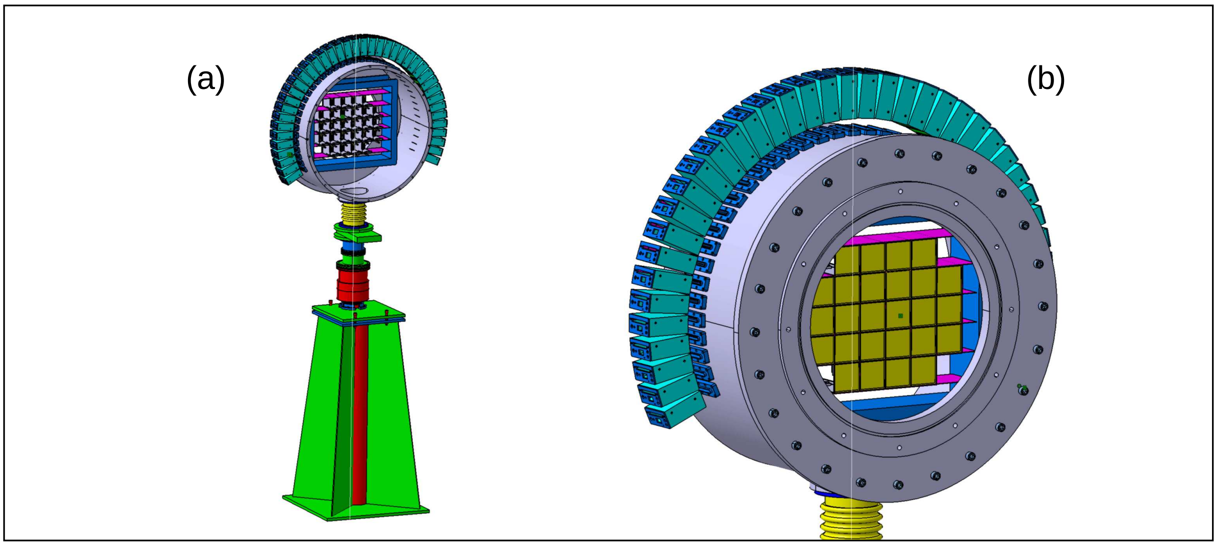

Figure 14: LYCCA detector chamber from the front and back side. The drawings include the radial assembly for the preamplifier boxes. Part (a) provides also the mechanics hosting the pumping system for the vacuum system.

The LYCCA-chamber is based on a cylindrical vacuum vessel with a diameter of 800 mm and a length of 400 mm. The upstream side will have an open circular entrance with a diameter of 450 mm for the incoming particles. The vacuum chamber is designed to host up to 26 detector modules [cf. Fig. 5(d)] consisting of fast timing detectors, DSSSD-detectors, and 9 CsI crystals per module.
Figure 14 shows an overview of the LYCCA detector chamber and the connection to the bottom including a pumping system. Surrounding the chamber are the preamplifier boxes for the different detector modules. Inside the chamber, the rectangular LYCCA main frame (dark blue) is fixed. Inside this main frame, six parallel, horizontal layers of submillimeter

thin steel metal sheets (violet) are stretched with high tension. Up to six LYCCA modules with about 63 mm ×63 mm ×200 mm in size each can rest on each of the five lower sheets. This scheme is highlighted in Fig. 15. If found necessary during the LYCCA-0 commissioning phase, a temperature stabilisation can easily be attached to the main frame through the bottom part of the chamber.

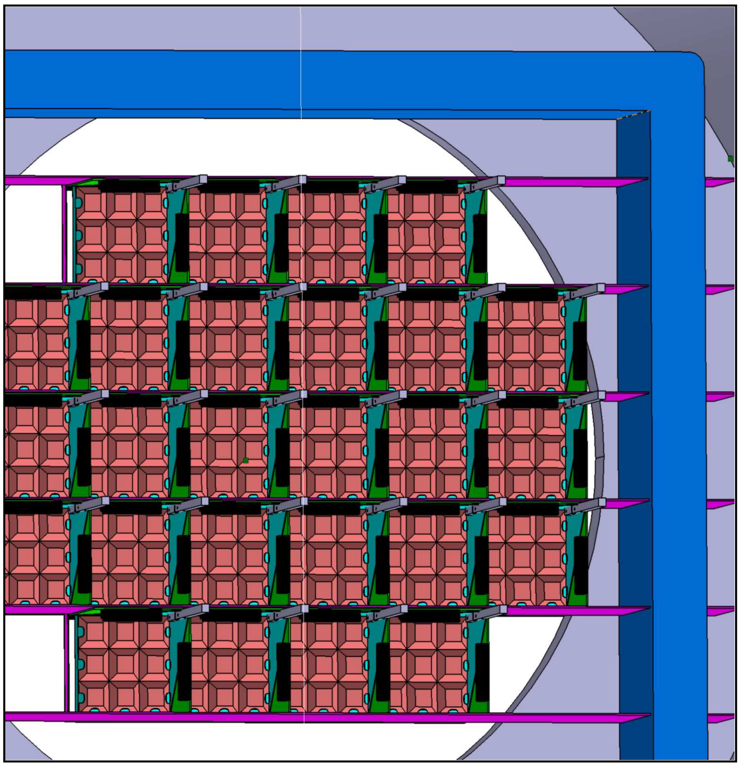

Figure 15: Detailed view of the LYCCA detector chamber from the back side. Six parallel planes (violet) are placed inside the LYCCA main frame (dark blue), separating the five layers for the individual detector modules. The subsets of the nine CsI crystals of each module are visible (pink) as well as the holding rods of each module (grey).

The mechanical mounting of the individual LYCCA modules is illustrated in Fig. 16. The printed circuit boards from the DSSSD (green) will be electrically isolated but mechanically fixed to an aluminum plate construction (cyan). A thin aluminum bar (5 mm ×5 mm ×150 mm) will be used to place and hold the module in its respective position on the steel sheets mentioned above. The aluminum construction also supports the DSSSD-PCBs and provides the connection to the aluminum housing for the CsI detectors. The CsI detectors are fixed with an aluminum angle bracket of sheet metal as indicated in the figure; the outer elements are supported by a folded piece of the aluminum metal. The inner element will be fixed by gluing its reflection wrapping foil to some of its neighbours. Some fine details of this constructions are still being discussed for ultimate optimisation. However, we consider the CATIA-5 based mechanical solution presented here being the proper basis for the LYCCA construction.

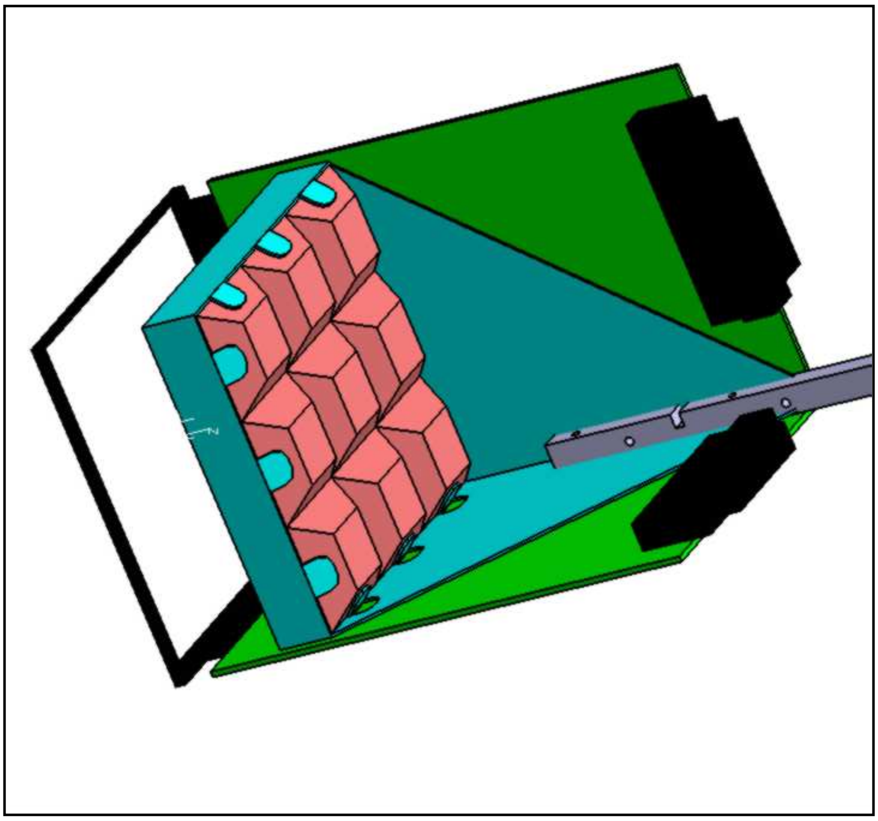

Figure 16: Details of fixing the CsI detectors (pink) in conjunction with the PCBs (green), which guide the signals of the DSSSD detectors. This is done by using an aluminum angle bracket (cyan) together with an aluminum bar (grey).

Note that the present construction also foresees the easy exchange of single LYCCA modules. For more details of the construction, please contact the head of the Cologne mechanics workshop, Mr. S. Thiel [21].
For completeness, two additional mechanics pieces are necessary for the LYCCA-0 PreSPEC phase. This is a revised bottom flange of the existing RISING Fast Beam target cross construction to both hold the target DSSSD and diamond detectors plus 2× 32 channel vacuum feed through and 1× 16 channel diamond detector feed through. Secondly, a beam pipe from the existing target cross to the new LYCCA chamber is needed. This part will start from the CF250 flange of the target cross. The beam pipe diameter will increase up to a diameter of 450 mm (no CF flange) within a length of 2000 mm. The final diameter of 450 mm is foreseen to be in accordance with HISPEC design studies. Between the end of this extension pipe and the beginning of the LYCCA chamber the plastic scintillator timing section needs to be mounted. This scheme is to be provided by GSI.

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5 Simulations

5.1 Overview

An application has been developed to simulate the response of the LYCCA detector system when used in conjunction with a fragment separator during two-step fragmentation reaction experiments. The application `lyccasim` can be broken down into three main parts: The first is the generation of events using the ion transport code MOCADI along with various scripts and programs to modify the output into a suitable format for the next stage. The second is the reading and tracking of the produced events onto and through the specified detector system. This part of the simulation is written using the GEANT4 framework. The third stage is the histogramming, analysis and storage of the produced detector signals. This is done using the ROOT data analysis framework where the required libraries and functions are accessed by the GEANT4 application code directly.

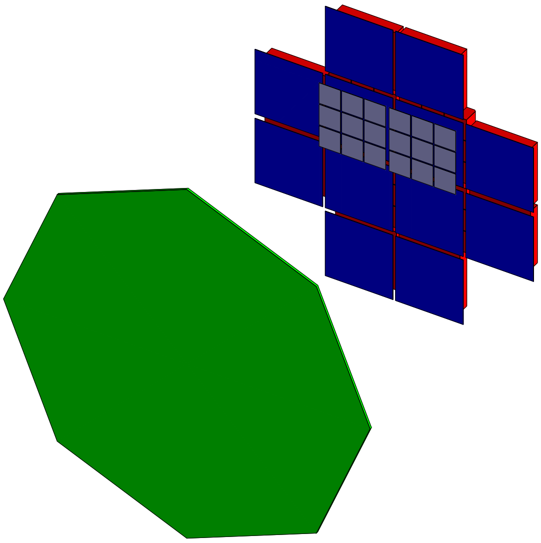

Figure 17: GEANT4 LYCCA-0 modules including a total of three stop timing options, namely a large-area fast plastic scintillator (green), CVD diamond detectors (grey), and also silicon itself (blue).

The simulated reaction is a two-step fragmentation reaction where a ^{58}Ni primary beam is incident on a ^{9}Be target. ^{55}Ni intermediate fragments are then selected by the FRS and impinge on a second ^{9}Be target producing a range of secondary fragments. This reaction was chosen as it matches that used during a RISING fast beam campaign experiment to study the mirror nuclei ^{53}Mn and ^{53}Ni. MOCADI has the ability to output variables characterising the produced fragments, such as energy and position, at various points in the specified set-up. This allows the user to not only incorporate the elements of a recoil separator such as magnets and tracking detectors but also simulate the signals produced by the tracking detectors, for example, the energy lost and interaction position. These descriptive variables are outputted to an ASCII text file which has to be modified to separate the incoming fragments, the intermediate fragments before the second reaction target, and the outgoing

fragments produced in the second fragmentation reaction. This stage is required as only the outgoing fragments are tracked by the GEANT4 simulation through the detector system but during the event file modification the correlations between in incoming fragment and outgoing signals are maintained.
The detector geometry is defined using the detector construction methods within the GEANT4 framework and the latest version of `lyccasim` has the LYCCA-0 geometry implemented including three different timing options, diamond-diamond, diamond-fast plastic, and even diamond-silicon. Figure 17 shows the defined LYCCA-0 detector geometries at the end of the TOF path.
The latest `lyccasim` version incorporates a simple XMotif GUI to control the simulation and issue commands to change key set-up parameters such as detector resolutions and the target-Si detector distance without the need to alter the source code and re-compile. `lyccasim` reads in the MOCADI generated secondary fragments and tracks the particles through the detector geometry. The detector signals created by the interaction of the fragments with the sensitive detector material are simulated and digitised. These signals, energy loss, position, and time are then passed to a ROOT analysis module where they are histogrammed and stored in a ROOT Tree object for further analysis. This allows the user to perform analysis on the simulated data in exactly the same way as one would on real experimental data.

5.2 Preliminary Results

As the chosen reaction matched that used in a RISING fast beam campaign experiment the simulation output can already be compared to existing real experimental data.

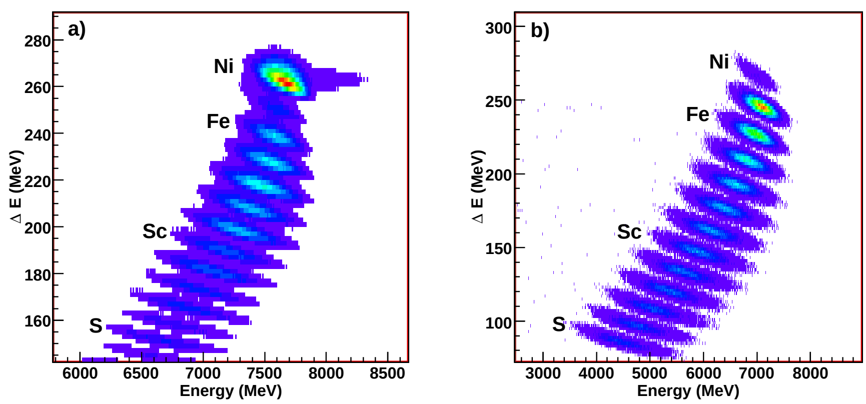

Figure 18: (a) Experimental data and (b) simulated data (LYCCA-0) using the same reaction as that for the experimental data.

Figure 18(a) shows the experimental data from the Si(ΔE)-CsI(E) telescope detector system (CATE) located at the focal plane of the FRS. Figure 18(b) shows the simulated data from the LYCCA-0 Si(ΔE)-CsI(E) detector system. The experimental data had a condition imposed that a γ-ray detected with the RISING Ge-detectors had to be in coincidence with a fragment implantation. Therefore, yield differences are observed between the two plots. The simulated data does not contain scattered ^{55}Ni beam particles either, unlike the experimental data. The Z identification of the detected fragments is good but different isotopes of a particular nuclear species clearly cannot be distinguished purely from a study of the total implanted energy. In order to achieve good fragment mass identification time-of-flight methods need to be considered along with the total implanted energy.

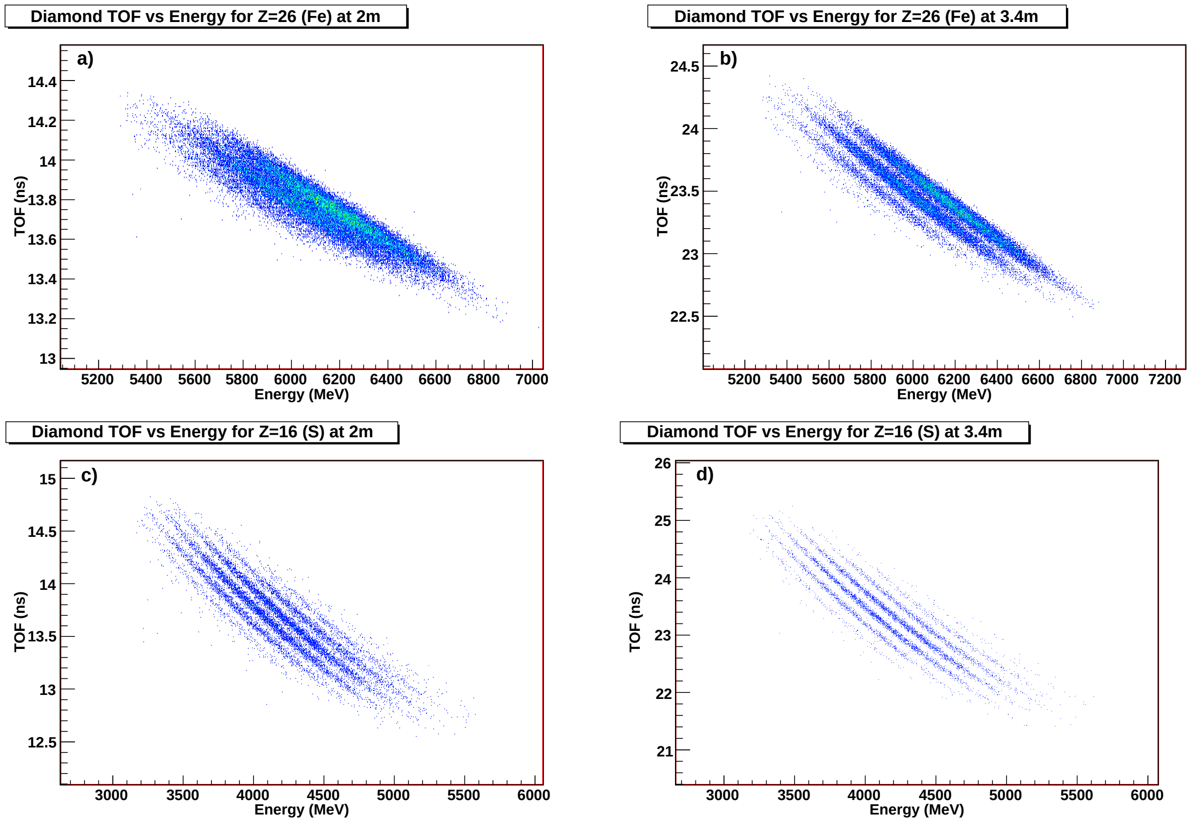

Figure 19: Time-of-flight vs total energy spectra for two different fragment species and two different flight paths. (a) Fe gated, 2 m flight path. (b) Fe gated, 3.4 m flight path. (c) S gated, 2 m flight path. (d) S gated, 3.4 m flight path.

Figure 19 shows results from the latest version of the `lyccasim`. Figure 19(a) shows a time-of-flight vs total energy plot for Fe gated fragments with a time-of-flight path of 2 m. Figure 19(b) shows the same as (a) but with a 3.4 m flight path. Figure 19(c) shows the same as (a) except for S gated fragments and Fig. 19(d) is the same as c) but with a 3.4m flight path. The TOF used in Figure 19 is determined using a 3 $\times$ 3 array of 19 mm $\times$ 19 mm, 200μm thick CVD diamond detectors located 1 cm behind the secondary reaction target as start timing detectors and two located 1 cm in front of the Si detectors as stop timing detectors. The nominal time resolution of these CVD diamond detectors is 50ps FWHM. The isotopic separation improvement for low mass fragments over higher mass fragments is evident as is the improvement due to the increase of the TOF path length. Note that the 3.4 m distance matches LYCCA-0, while LYCCA will be placed 4 m, 9 m, or some 15 m behind the secondary reaction target (cf. Fig. 1).
The results in Fig. 19 are not yet corrected for some (minor) correlations of the incoming energy of the fragment beam particle with the outgoing energy of the final fragment of

interest. In addition, the x-axes provide the sum of ΔE signals measured with the DSSSD detectors ($\Delta E/E = 1.0$ %) and the E signals from the CsI wall ($\Delta E/E = 0.5$ %). Hence, there is further room of improvement on the prospected mass resolution for LYCCA, which is presently evaluated in more detail with the help of our advanced simulation scheme.
The simulation is thus constantly being updated and improved as results from detector testing become available. It will then be cross-checked with the experiments within the 'LYCCA-0 + RISING' campaign in 2009 and 2010 and will finally be used to simulate the response of the full LYCCA system when coupled to the Super-FRS for a range of prospected HISPEC and/or DESPEC experiments.

6 Radiation Environment and Safety Issues

LYCCA is going to be operated in the NuSTAR Low-Energy-Cave, which will see low-intensity primary and secondary radioactive ion beams. Hence, both short-lived and accumulated radioactivity is at a comparatively low level as at, for example, the present S4 focal plane area of the FRS at GSI. Therefore, no specific radiation safety actions are foreseen besides the by then implemented restricted access procedure for the cave during beam times. LYCCA does not include any cryogenic cooling devices or other mechanical hazards, the latter to the best of our knowledge. The high-voltage supplies for the different CsI, Si, and diamond detectors do not exceed a few hundred volts at very low currents.

7 Quality Assurance and Acceptance Tests

Due to the proposed staged process of the production of LYCCA modules and the overall rather limited amount of individual detector elements, both their assembly, quality assurance, and acceptance tests will be performed by the LYCCA collaboration itself on test benches in Lund (CsI and DSSSD) and York (diamond) using standard radioactive sources.
From the very beginning the modules will be used in physics driven campaigns at the present S4 area of the FRS and most likely to commission the different sections of the new Super-FRS, which in turn commissions the LYCCA modules themselves. If needed, other test beam facilities at GSI and the University of Cologne exist.

8 Calibration

There are established in-beam calibration procedures from previous and coming campaigns. They have to be done for each experimental campaign, which requires typically one shift of beam time. These procedures are coupled to campaign-specific calibrations of FRS and Super-FRS detector elements.

9 Civil Engineering and Installation

The LYCCA chamber and associated couplings are going to be produced primarily in the mechanics workshop of the University of Cologne and possibly at GSI. LYCCA modules will be assembled, cabled and source tested at Lund and York.
The transportation will be done by standard procedures of partially highly fragile instruments from the various assembly and test laboratories to GSI/FAIR. For the chamber and stands from Cologne to GSI neither size nor weight require very specific handling. The detector modules are small and relatively easy to handle as well. Most likely, even they are going to be brought to GSI by car in properly packed boxes.
Installation at GSI/FAIR will be done in the respective laboratory spaces, i.e. the placement and cabling of the detector modules inside the chamber. Note that this has to be done already for the LYCCA-0 campaign envisaged for 2009, i.e. by the time of FAIR beams, only additional modules will have to be added or remounted inside the chamber. Due to the overall mounting scheme, this could be done even with the chamber in place of the experiment position.
The chamber as such, with or without detector modules inside, can be easily transported within GSI/FAIR on proper carts. Fixing the chamber at the experiment position requires the use of the standard cranes existing (S4 area) or planned (M4 area, Low-Energy Cave).
The electronics racks are going to be place in near vicinity of the LYCCA chamber, i.e. the cabling can be done easily with standard procedures.

10 Funding

Note that prototyping and production of LYCCA-0 has been made possible by combining efforts of efficient (re)use of existing detectors and electronics modules, running grants such as RISING running costs or Swedish S-FAIR planning money, as well as specific small-scale grant applications to mainly Swedish foundations.
The (physicist's) idea is to split the FAIR Cost Book money associated to LYCCA in terms of 45%:45%:10% Sweden:UK:Germany.

Note that a basic acceptance of this TDR is required by both the Swedish and UK authorities to release the bulk investment money towards LYCCA.

10.1 LYCCA-0

DSSSD and CsI prototyping: Crafoordska foundation, Lund, Sweden.
DSSSD timing prototyping: RISING running costs.
Diamond detector prototyping: early UK-FAIR money
Plastic scintillator: GSI, RISING running costs, and Fysiografen, Lund, Sweden.
Mechanics planning: Cologne workshop.
Mechanics construction: Cologne and GSI workshop.
Remaining DSSSD detectors: running Swedish grants and RISING running costs.
Remaining small CsI detectors: running Swedish grants.
Electronics: distributed, see Table 5.

Research engineer Lund: S-FAIR planning money.
PhD student: GSI and Lund, Sweden

10.2 LYCCA

(assumes diamond ToF)

DSSSD and CsI detector modules: S-FAIR.
Diamond detectors: UK-FAIR.

DSSSD ASIC (additional AIDA chips): UK-FAIR.
CsI S-ADCs or ASIC: S-FAIR.
Diamond ASIC (additional TACQUILA chips/channels): UK-FAIR or GSI.

Electronics planning: UK-FAIR, NuSTAR DAQ group
Mechanics planning (lcp-array and possibly spectrometer chamber): UK-FAIR.
Mechanics construction: Cologne workshop.

Research engineer Lund: S-FAIR.
PhD students: UK-FAIR, running Swedish grants, GSI.