Technical Report
for the Design, Construction and Commissioning of the
HISPEC/DESPEC Beam Line, Infrastructure and Tracking
Detectors

TDR 2_04
Technical Report

For the Design, Construction and Commissioning of the HISPEC/DESPEC Beam Line, Infrastructure and Tracking Detectors.

PREAMBLE

The NUSTAR experiments are organized along different branches each with several experiments and served by the Super-FRS as a separator of the rare isotope beams of FAIR. For this reason, the subdivision into different TDRs is rather complex. The TDR described in this document deals with the infrastructure directly related to the HISPEC/DESPEC (H/D) experiment.

The H/D experimental area will be located in the low-energy branch (LEB) of the Super-FRS (among other experiments which are not described in this TDR as the Cryogenic Stopping Cell, MATS, LASPEC and Super-FRS experiment collaboration). The infrastructure of the whole LEB will be available to all experiments and the related LEB TDR will include the description of the experimental areas, including size, placement of electronic racks and containers. The LEB TDR is under preparation, independently of this H/D infrastructure TDR. The electrical installation, gases, liquids, ventilation, as well as cranes and other general purpose infrastructure will be described in the general building specifications which is presently being finalized and discussed (among others) with the authors of this TDR.

In this document referrals are often made to the Super-FRS TDR, which contains the description of all spectrometer components, including all focal planes, also those in LEB. In particular, the tracking detectors, vacuum chambers and other general purpose instrumentation for separation/identification of rare-isotope beams in those focal points are described there and are updated in “detailed specifications” documents available on EDMS. All related documents are referred to in this TDR. Similarly, the information from the NUSTAR DAQ TDR is often used in this document.
In this document it is specified whether a given detector or infrastructure item is available in the building specification, the LEB TDR, the Super-FRS TDR, “detailed specifications” document or is introduced in this document. Only specific tracking detectors and infrastructure used by H/D collaboration are described in detail in this TDR. Most are in the LEB experimental area. The H/D collaboration would like to contribute to the general purpose detector pool with a FINGER detector in the middle focal point of the Super-FRS (FMF2). The full description of this tracking detector as well as other H/D specific tracking detectors is given in this TDR.

Abstract

HISPEC/DESPEC (H/D) experiments will be situated in the Low Energy Branch (LEB) cave of the NUSTAR collaboration within FAIR. The goal of the H/D experiments is to investigate the structure of exotic nuclei far off stability. The Superconducting-Fragment Separator (Super-FRS) and its tracking detectors and devices will be used for successful production, separation, and selection of these isotopes, to be investigated by means of in-beam and decay spectroscopy. The general H/D setups are presented for all phases of FAIR: 0, 1, 2. The components of the beam line including the target chamber and/or stopper are explained. The incoming beam will be identified event-by-event in the Super-FRS before arriving to the LEB. However, to satisfy the specific requirements of the secondary beams for H/D experiments redundant measurements are often needed to guarantee the proper identification in the energy range of interest. Those requirements are described. The special settings of the Super-FRS for the optimized intensity of the secondary beams at the LEB will require exceptionally high rate acceptance at the FMF2 focal plane. Detector infrastructure requirements are given here and are shown to fit in the design of the LEB. Additional requirements necessary to host and accommodate the AGATA spectrometer in the setup are presented as well. Safety issues are also addressed. The different aspects of this TDR are discussed in terms of subsystems in common tables.
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**Table 1: HISPEC/DESPEC infrastructure subsystem, institute and contact persons.**

<table>
<thead>
<tr>
<th>Subsystem ID/PSP code</th>
<th>Subsystem</th>
<th>Institute</th>
<th>Participants (contact persons in Bold)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.2.2.1</td>
<td>Common beam tracking</td>
<td>GSI Darmstadt</td>
<td>M. Górská, C. Nociforo, H. Weick, P. Boutachkov, S. Saha, J. Vesic, F. Ameil, S. Pietri, O. Kiselev N. Marginean J. Jolie N. Pietralla, V. Werner M. Lipoglavsek</td>
</tr>
<tr>
<td></td>
<td></td>
<td>IFIN-HH Bucharest</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>IKP Cologne</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>TU Darmstadt</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>IJS Ljubljana</td>
<td></td>
</tr>
<tr>
<td>1.2.2.1.5</td>
<td>FINGER detector</td>
<td>IFJ PAN Krakow</td>
<td>P. Bednarczyk, J. Kotula, A. Czermak, A. Kotarba M.L. Cortes, J. Gerl, S. Saha, J. Vesic</td>
</tr>
<tr>
<td></td>
<td></td>
<td>GSI Darmstadt</td>
<td></td>
</tr>
<tr>
<td>1.2.2.1.4</td>
<td>Slow-down beam tracking (MCP-SED)</td>
<td>IKP Köln</td>
<td>J. Jolie, M. Cappellazzo P. Boutachkov, M. Górská, J. Vesic J.Gomez Camacho, B. Fernández</td>
</tr>
<tr>
<td></td>
<td></td>
<td>GSI Darmstadt</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>CAN-Univ.Sevilla</td>
<td></td>
</tr>
<tr>
<td>1.2.2.2</td>
<td>H/D Beam line</td>
<td>GSI Darmstadt</td>
<td>M. Górská, I. Mukha, S. Saha, P. Boutachkov D. Rudolph N. Pietralla, V. Werner M. Lipoglavsek N. Marginean</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Univ. Lund</td>
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<tr>
<td></td>
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<td>TU Darmstadt</td>
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<tr>
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<td>IJS Ljubljana</td>
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<tr>
<td></td>
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<td>IFIN-HH Bucharest</td>
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<td>1.2.2.3</td>
<td>Mechanics</td>
<td>GSI</td>
<td>M. Górská, P. Boutachkov, I. Kojuharov, S.Saha, H.J. Wollersheim, J.Gerl P. Bednarczyk, J. Kotula, M. Curyło, J. Blocki, P.Wąchal J. Simpson, A. Grant, I. Burrows</td>
</tr>
<tr>
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<td>IFJ PAN Krakow</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>STFC Daresbury</td>
<td></td>
</tr>
<tr>
<td>1.2.2.5</td>
<td>Safety</td>
<td>GSI</td>
<td>M. Górská, I. Kojuharov</td>
</tr>
<tr>
<td>1.2.2.6</td>
<td>Cabling</td>
<td>GSI</td>
<td>S. Pietri, H. Schaffner</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Univ. Liverpool</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>STFC Daresbury</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>IFJ PAN Krakow</td>
<td></td>
</tr>
<tr>
<td>1.2.2.4</td>
<td>DAQ H/D</td>
<td>GSI</td>
<td>S. Pietri</td>
</tr>
<tr>
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<td></td>
<td>IFJ PAN Krakow</td>
<td></td>
</tr>
<tr>
<td>1.2.2.2</td>
<td>Infrastructure</td>
<td>GSI Darmstadt</td>
<td>I. Kojuharov, F. Ameil, S. Pietri</td>
</tr>
<tr>
<td></td>
<td></td>
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</tr>
</tbody>
</table>
The infrastructure for the HISPEC/DESPEC (H/D) experiments including detector infrastructure required for tracking and identification of secondary beams, mechanics, beam line components, cabling, DAQ control systems and safety is described in this TDR. The detector requirements are supported by simulations. The report is organized in the following order. In Chapter 1, an overall introduction to the experimental campaign is given. In Chapter 2, the physics motivation, the different kinds of planned experiments and the detector systems required are introduced. The specific detector requirements in different focal planes for H/D experiments are explained in chapter 3. In chapter 4, the status of the prototype detectors is specified. The simulation results are described in chapter 5. The technical specification of prototype detectors and other infrastructures are detailed in chapter 6. Chapter 7, 8 and 9 explain safety issues, production and quality assurance of the prototype detectors, and calibration respectively. The engineering requirements, installation procedure, and costs are reported in chapter 10, 11 and 12 respectively.

The report is based on the scientific knowledge and expertise gained in the past H/D experiments at the FRS and are supported by simulations performed for the Super-FRS. The description of the preceding focal planes of the Super-FRS are not described in this report. The details of some H/D detector systems, such as AIDA, LYCCA, DEGAS etc., are not included in this report as they have already been described in detail in other detector specific TDRs. This report will guide the planning of future experiments of the H/D campaigns at the NUSTAR-LEB.

Contributors to this report are:

1. Introduction and Overview

The H/D experiments will address questions in nuclear structure, reactions and nuclear astrophysics, by in-beam and decay spectroscopy. Germanium detector arrays based on cutting edge technologies and other sophisticated γ detectors are being employed, complemented by a suite of detector systems for charged particles and neutrons as well as devices dedicated to specific types of nuclear structure observables such as single-particle strengths or electromagnetic moments, to name but a few.

At the low-energy branch (LEB) of the Super-FRS, beams of radioactive ions with energies of typically 10-200 MeV/u will be available for in-flight experiments (HISPEC) as well as stopped beam for decay experiments (DESPEC).

**HISPEC**
The standard HISPEC (High-resolution In-flight SPECtroscopy) setup will comprise inter alia beam tracking and identification detectors and the AGATA [1] Ge array to measure γ rays arising from nuclear states excited in the course of secondary reactions of the radioactive beams. This can also involve charged particle detectors (HYDE) or a plunger device for direct state lifetime measurements around the secondary target. The outgoing radioactive species are event-by-event identified by time-of-flight, energy loss and total energy using the Lund-York-Cologne CALorimeter (LYCCA) [2] and a magnetic spectrometer. LYCCA is a core device for the HISPEC program. The precursor, LYCCA-0, has already been in use at GSI, and serves also as the basis for FAIR. Additionally, some HISPEC experiments will be performed with a FAst TIMing Array (FATIMA) [3] coupled to or in place of AGATA and a NEutron Detector Array (NEDA) [4]. Phase 0 of HISPEC (HISPEC-0) started already with a campaign at GSI, using the FRS, AGATA demonstrator, and LYCCA-0 under the name of PreSPEC [5][6].

**DESPEC**
In DESPEC (DEcay SPECtroscopy) experiments, the radioactive ions are stopped in a highly segmented silicon-based, implantation and decay detector system (AIDA) [7]. This system will be surrounded by a compact high-resolution Ge detector array (DEGAS) [9], neutron detectors, fast-timing LaBr₃ detectors or a total absorption γ-ray spectrometer. A magnet for isomeric moment measurements is an additional option for the later phases of FAIR. Here, decay studies of near drip line nuclei with extreme neutron/proton ratios will be the core interest, in particular towards the neutron-rich r-process lines. The Phase 0 of DESPEC (DESPEC-0) will be realized at GSI and FRS including AIDA, FATIMA, DTAS [8], DEGAS [9] and MONSTER [10] in the years 2018-2023.

It will also be possible to combine HISPEC and DESPEC for recoil decay studies, with the DESPEC detectors being placed at the end of the magnetic spectrometer in the LEB.

Additionally, a slowdown beam campaign is planned to be carried out in a later phase of HISPEC. In this campaign, the beam will be slowed-down to energies in the vicinity of the Coulomb barrier before incident on an active stopper placed at the center of the γ-array (e.g. AGATA) to have (multistep-) Coulomb excitation of the fragments and to observe the decaying γ rays. The objective
of slowdown experiment will be to study the nuclear structure around the Coulomb barrier (*i.e.* high spin and single particle structure), dynamical properties, transition probabilities, and moments.

HISPEC and DESPEC experiments have much in common in terms of both the physics and the instrumentation, for instance they will use the same suite of ion identification and tracking detectors, the same beam line including general support structures for γ ray arrays mounted on exchangeable platforms on rails. They will also use common infrastructure for detectors and their mechanics when possible. The common parts of HISPEC/DESPEC infrastructure and tracking detectors addressed in this paper are summarized in Table 2. FAIR phase-0 experiments at GSI, i.e. PRESPEC (HISPEC-0) and DESPEC-0 are treated in this TDR as well.

**Table 2: The required subsystems for H/D beam line infrastructure for a given phase of FAIR.**

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Requirements on</th>
<th>Details</th>
<th>Phase of FAIR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Common beam tracking</td>
<td>Rate, area acceptance</td>
<td>Same as Super-FRS, MUSIC, degrader, TPC</td>
<td>1</td>
</tr>
<tr>
<td>FINGER detector</td>
<td>Rate, area acceptance</td>
<td>&gt;1MHz rate</td>
<td>0,1</td>
</tr>
<tr>
<td>Slow down beam tracking</td>
<td>Rate, area acceptance, thickness</td>
<td>&gt;100kHz rate</td>
<td>2</td>
</tr>
<tr>
<td>HISPEC Beam line</td>
<td>Standard Super-FRS tubes</td>
<td>Ø 400 mm, at the target area Ø 200 mm</td>
<td>1</td>
</tr>
<tr>
<td>DESPEC Beam line</td>
<td>Standard Super-FRS tubes</td>
<td>Ø 400 mm, air before the implantation</td>
<td>1</td>
</tr>
<tr>
<td>Mechanics</td>
<td>Platforms, rails, supports (detector tables), pumps</td>
<td>FRS-S4, FLF3, FLF4, FLF6</td>
<td>0, 1, 2</td>
</tr>
<tr>
<td>AGATA</td>
<td>AGATA geometry</td>
<td>Frame adaptation for 2π geometry and beam height of 2m</td>
<td>1</td>
</tr>
<tr>
<td>Safety</td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Cabling</td>
<td></td>
<td></td>
<td>1</td>
</tr>
</tbody>
</table>
2. Physics requirements and experimental systems

Investigation of exotic nuclei far away from the valley of stable isotopes is one of the frontier topics in the study of the atomic nucleus. The production, detection and measurement of short lived and rare nuclei is an experimental challenge, which will be tackled by the Super-FRS+H/D facility at FAIR. The accelerator facility will produce isotopes of all elements up to uranium with energy as high as 1.5 GeV/u. The high Bρ and good momentum acceptance of Super-FRS will allow the production of heavy unstable isotopes using fragmentation and fission. Different kinds of measurements could be performed to understand the reaction, structure and astrophysically important properties of the yet unexplored territory of the nuclear landscape. Broadly, H/D will perform decay measurements of α, β, γ, proton and neutron radiation emitted from unstable isotopes. In the Super-FRS the isotopes will be separated and identified on an event by event basis using various tracking detectors and then transported to the LEB. Finally, these fragments will be implanted in an active stopper for the study of various decay modes (DESPEC). The corresponding excited states of the daughter nucleus to which the fragments decay into will be studied by observing the subsequent particle/γ emission during the deexcitation to the ground state. The other possibility is to excite the fragments via reaction processes on a secondary target and to observe the γ rays in flight from the subsequent deexcitation (HISPEC).

Figure 1. Schematic layout of the Low Energy Branch of the Super-FRS.
Figure 2. Technical layout of the LEB as planned by the general building specifications
The LEB of the Super-FRS has a number of focal planes and separation stages. The relevant focal planes for H/D experiments are identified as FLF2, FLF3, FLF4, and FLF6 (see Figure 1). In Figure 2, the technical layout of the LEB cave is given as planned by the general building specification (GBS). Various types of detectors are planned to be placed at these focal planes. They will be used for identification and tracking of the fragment of interest. The block diagrams and schematic drawings of these detector setups are described in Chapter 3.

The principles applied for the fragment identification will be the same as in previous campaigns at GSI/FRS. The beam particles entering the LEB have to be identified and their position and angles at different focal planes need to be measured event by event. The detector configuration at FLF2 will be the same for all types of experiments. A/Q for fully stripped fragments will be deduced from the Bp of the separator stage and the velocity of the fragments. Precise, event by event time of flight (TOF) measurement of the fragments is required to calculate their velocity $\beta = v/c$ and $c$ being the speed of light). The TOF measurements will be carried out between FMF2, the middle dispersive focal plane of the Super-FRS (for details please refer to the Super-FRS TDR and Super-FRS vacuum diagnostic chambers on focal planes of the Super-FRS detailed specification document[11]) and FLF2 in the same way as in S2 and S4 of the FRS. The timing detectors (also referred to as scintillator in this document) are required to have excellent time resolution ($\sigma \sim 50$ ps ) and high count-rate capabilities (up to $10^6$ pps/cm) especially at FMF2. To cope with such stringent requirements, segmented plastic detectors, so-called FINGER detectors [12] are being developed for the FMF2 and FLF2 focal planes. For optimal mass resolution the measured TOF will be corrected for the position and angle of the fragments with respect to the beam direction. For this purpose and for the Bp determination, the Super-FRS tracking detectors [13] (will be hereafter refer to as the Time Projection Chamber (TPC)) will be used at the FMF2 and FLF2 focal planes. Additional TPCs to determine the trajectory of the secondary fragments, will be positioned at FLF3, FLF4, and FLF6 depending on the experiment being performed. The Z identification will be carried out by two Super FRS MUSIC ionization chambers (will be hereafter referred to as the twin-MUSIC or MUSIC) placed one after another at FLF2, which will have a rate handling capability of up to 1 MHz [14].

The major difference in the design of the beam-line infrastructure of the LEB from that at GSI/FRS is the acceptance of the magnets along the Super-FRS and therefore the possible beam spot size at the focal planes. The FLF3 focal plane at the LEB cave will have a dimension of $(x,y) = (240,100)$ mm. Therefore, at least such an area should be covered by each beam tracking detector placed in this cave. The individual detector sizes will be specific to the requirement of particular experimental setups.

Special requirements are needed for the FINGER detector to be placed in the intermediate focal plane FMF2 as a start TOF detector. There the maximally expected rate estimated for the secondary
beam is above 1 MHz. It’s area should also be adjusted to this dispersive focal plane i.e. to suit other tracking detectors e.g. the newly developed GEM TPC [13] with (x,y)=(380,80) mm.

In addition to the tracking and identification detectors introduced above, for different experimental campaigns, different kinds of detectors will be required at FLF3. In the DESPEC measurements, the ions from the separator will be implanted into AIDA, acting as an "active catcher" made of highly segmented double-sided silicon-strip detectors. The total beam particle rate will be at most 10 kHz and for many experiments < 1 kHz. The exotic nuclei then disintegrate by radioactive decays. The high pixelisation of the silicon detectors will allow correlation of the time and position of the implanted heavy ion with the signal produced in the same detector via subsequent α or β decay. The deexcitation of the daughter nuclei via γ decay will be observed by DEGAS, DTAS, or FATIMA arrays: The high-resolution DEGAS array will be used to identify the γ ray energies and correlations, while FATIMA will be used for lifetime measurement based on the time distribution of the detected γ rays. DTAS will be used as a total absorption spectrometer for γ rays. Finally, neutrons will be detected by the BELEN [20] or MONSTER detector arrays.

The expected secondary beam rate in HISPEC experiments at FLF3 is at maximum 100 kHz and all tracking detectors should withstand such rates. This, however, goes in line with the general requirement for the Super-FRS tracking detectors. The use of the current AGATA scattering chamber in HISPEC experiments, with its 35.4 cm diameter, will require a smaller tube section (16 cm) after the tracking detector chamber. The full AGATA geometry limits exit tube of the AGATA scattering chamber diameter to 10 cm, hence only 8x8 cm² target will be used without sacrificing too much efficiency.

Measurements of Coulomb excitation and secondary fragmentation reactions of rare fragments are the primary goals of the HISPEC experiment. In addition to high efficiency γ and neutron detection, tracking and identification of outgoing fragments will be required. For this purpose, the fragments excited at the secondary target at FLF3 will be transported to the next focal plane FLF4. The magnetic elements between FLF3 and FLF4 will be used as a mass spectrometer. Special detector assembly at FLF3 behind the target and at FLF4 will be required for measurement of Z and A/Q for the outgoing fragments. The detector assembly is known as Lund-York-Cologne CAlorimeter (LYCCA) [2]. The A/Q will be determined from the position at FLF4 and ToF of the fragments. To determine the position of the fragment at the secondary target a Double Sided Silicon Strip Detector (DSSSD) will be placed before the target. Thereafter, a ToF start scintillator detector will be used. At FLF4, a ToF stop scintillator and a ΔE-E detector will be placed. The ΔE-E measurement will be performed by DSSSD and CsI(Tl) detectors. The combination of the magnetic spectrometer with LYCCA ToF, ΔE, and E measurements and the possible use of other tracking detectors is going to allow for A and Z discrimination up to the heaviest isotopes.

A high Z target material of appropriate thickness will be used for Coulomb excitation of the fragments. The coincident γ rays emitted by the de-excitation of the nuclei will be detected by an array of γ-detectors surrounding the target (e.g. AGATA detectors). The determination of reaction kinematics, Doppler correction, charge and mass identification of the reaction products will be performed by a combination of a position sensitive ToF detector and position sensitive ΔE-E-
telescopes surrounding the target.

3. Detector and infrastructure configuration

3.1 FMF2 focal plane

A number of general purpose devices will be used at the FMF2 focal plane for the selection and identification of fragments such as TPCs, scintillators and degrader. In Figure 3, a technical drawing of the FMF2 focal plane chamber housing these devices is provided. Development of these detectors is the responsibility of the Super-FRS machine project and is described in the Super-FRS TDR \[11\]. However, the FINGER detector for the detection of the start TOF signal is provided by the H/D collaboration. The general requirement for all active detectors for H/D experiments is sufficiently high count rate handling capability (> 1 MHz/cm). This requirement has made the development of new beam tracking detectors capable of dealing with high count-rates utmost importance. In particular, for the ToF determination plastic scintillation detectors are a good choice as they provide very quick response, excellent time resolution, are easy to manufacture in a wide variety of shapes, have a reasonable price and proved reliable since decades in many different experiments involving heavy-ions.

**Figure 3.** Technical Drawing of FMF2 focal plane chamber as planned for Super-FRS (see Super-FRS TDR [11,19]), showing the space allocated for the FINGER detector.
3.1.1 Design requirements of the FINGER detector

Prototypes of the FINGER detector have been developed for HISPEC-0 [12] and DESPEC-0 [21] at GSI. The major difference in the FINGER design for Phase-1 at FAIR is the increased acceptance of the magnets along the Super-FRS, which imposes a much bigger detector size to cover the beam spot size. In addition, the detector should be able to cope with the high beam intensities as $10^7$ pps. Most importantly, the intrinsic time resolution of the detector has to be sufficient to perform an adequate $A/Q$ identification. A summary of the requirements for the detector is given below.

- **Spatial coverage and granularity:**
  The area covered by the FINGER detector should be suited to the dispersive focal plane FMF2. The dimensions of the detector active area in the $(x,y)$ plane should be at least $(380, 100)$ mm. The granularity of the detector is defined by the width of the strips. A width of 4.5 mm is recommended to keep a balance between the high rate capability and the easiness to handle the detector. This gives a minimum of 85 plastic scintillator strips. In order to ensure proper coverage 90 strips of 4.5 mm are recommended.

  The full assembly of detector components with mechanical holding structure has to be less than 34 cm wide in the dispersive plane to fit in the space allocated at the FMF2 focal plane. As the strips and light guides are only a few mm in thickness, the aforementioned requirement is important only for the design of the mechanical structure holding the PMTs. In the future, also SiPM are considered as a possible option for the design.

- **Time resolution and rate capability:**
  The time resolution of the FINGER detector directly affects the achievable $A/Q$ resolution. This resolution depends on the rise time of the signal from the plastic scintillator, on the optical systems used to transport the signal to the PMT (i.e. light guide) and on the electronics used to read-out and process the signals. In the Phase-0 FINGER detector a time resolution of $\sigma = 70$ ps has been achieved. Preliminary analysis of data collected using a new prototype FINGER detector points to a similar value. The time resolution can be improved further by time walk correction of the used leading edge discriminator. Offline subtraction of correlated/uncorrelated crosstalk events can also improve the timing. For the future Phase-1 FINGER detector a time resolution of $\sigma = 50$ ps should be achievable. The limitation in terms of rate capability is given by the saturation of the PMTs. This saturation usually occurs at around $10^6$ pps. Thanks to the segmentation, the overall FINGER detector rate is distributed among many strips. In consequence, the expected rate capability of the FINGER detector is around $2 \times 10^6$ pps/ cm.
● **Energy resolution:**
It is expected that there will be transmission of some photons from the scintillating strip to the neighboring PMT’s leading to optical crosstalk. The energy resolution should be sufficient to reject the crosstalk events.

● **Homogeneity:**
Careful mounting of strips will be required to avoid gaps between the strips and to achieve the best efficiency.

● **Position resolution:**
The position resolution of the FINGER detector is given by the size of the strips. It is to note that the FINGER detector is not foreseen as a position detector, nevertheless if necessary it can also be used as such but with somewhat limited A/Q determination.

● **Versatility:**
Due to the radiation damage of the plastic scintillators expected during or after each experiment, it is of utmost importance that the detector strips can be easily replaced. Similarly to the existing detector, the new FINGER detector will have the strips mounted in a frame which can be easily removed and replaced from the top of the chamber holding the mechanical assembly.

### 3.2 FLF2 focal plane
A number of different detectors will be required at the FLF2 focal plane for beam tracking and identification purposes. Besides the FINGER detector (additional and smaller than that at the FMF2 focal plane) and the timing scintillator, which are the responsibility of the H/D collaboration, all other detectors are provided by the Super-FRS project as described in the Super-FRS TDR [11] and Ref.[19]. The placement of these detectors at FLF2 is shown in Figure 4. The detectors provided by Super-FRS are two TPCs for position measurement in the XY plane, one MUSIC detector for charge state identification and one Si Time-of-flight (TOF) detector. As there will not be any X slits before the TPCs, the device should be calibrated without any additional requirement of references. The minimum energy requirement for Z identification of the fragments with Z > 50 in the MUSIC detector is 400 MeV/u. In order to maintain this requirement even for heavier isotopes, additional degraders at FLF2 and FLF3 focal plane are foreseen to further slowdown the beam depending on the experimental requirements. The position and angle obtained from the twin TPCs will be used to correct the path lengths of fragments travelling in a non-central trajectory within the focal planes of the separator. The combination of TPCs and MUSIC is essential for Z identification with good accuracy. The Si TOF detector (described in the Super-FRS TDR [11]) or the FINGER detector will be used for STOP timing measurement. Placing the FINGER detector in air will allow easy replacement of the FINGER plastic strips whenever necessary. Except for the FINGER detector, all the other detectors and degraders will be kept in vacuum (as described in the Super-
FRS TDR [11,19]). In addition, there will be provision a for an X slit [15] and a Y slit, which can be used to restrict the accepted fragments. The dimensional requirements of the TPC’s, MUSIC, TOF [16] and Degrader are given in Table 3. The X-Y dimensions of the TPC, MUSIC, Si-detector and the degrader are based on MOCADI simulation carried out using production and identification of the $^{214}\text{Pb}$ and $^{106}\text{Sn}$ fragments in the Super-FRS.

Table 3. The general purpose devices requirement at FLF2 focal plane:

<table>
<thead>
<tr>
<th>Detector</th>
<th>Length in X (in mm)</th>
<th>Length in Y (in mm)</th>
<th>Chamber Length in Z (in mm) [19]</th>
<th>Energy requirement (MeV/u)</th>
<th>Count Rate (pps)</th>
<th>Super-FRS Provided</th>
</tr>
</thead>
<tbody>
<tr>
<td>2xTPC</td>
<td>380</td>
<td>80</td>
<td>450</td>
<td>&gt;200(Super-FRS specifications)</td>
<td>&gt;10$^6$</td>
<td>X</td>
</tr>
<tr>
<td>MUSIC</td>
<td>380</td>
<td>80</td>
<td>750</td>
<td>&gt;400(Super-FRS specifications)</td>
<td>&lt; 10$^6$</td>
<td>X</td>
</tr>
<tr>
<td>Si-TOF</td>
<td>200</td>
<td>60</td>
<td>350</td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Degrader</td>
<td>350</td>
<td>100</td>
<td>550</td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>FINGER</td>
<td>300</td>
<td>100</td>
<td>350</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scintillator</td>
<td>380</td>
<td>100</td>
<td>350</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 4. Block diagram of FLF2 focal plane insertion. (Block size not to the scale)

3.3 FLF3 focal plane

Several detector configurations will be required at FLF3 in order to perform the different planned experiments. Furthermore, the beam dimensions at the FLF3 focal plane will also vary for HISPEC and DESPEC experiments. The different experimental setups and the corresponding tracking detectors required are presented in the following. The required major detector components are listed in Table 4.

3.3.1 HISPEC-200 experiment

The HISPEC experiments will use AGATA, FATIMA and/or NEDA coupled to LYCCA. The dimensions of the secondary target at the center of AGATA array will be 7 x 7 cm² and several 100 mg/cm² thick. A schematic diagram of the FLF3 focal plane with different detectors required for the AGATA experiments is shown in Figure 5/a.

For certain experiments the secondary target may be replaced by a Liquid-Hydrogen (LH2) target surrounded by a tracking system allowing to track recoil protons from (p, 2p) type reactions and to reconstruct the reaction vertex in the target on an event-by-event basis. The design is based on the MINOS detector (see Figure 5/b) [17], but the annular time projection chamber (TPC) will most likely be replaced by Si strip detectors to allow for a more compact design which would fit into AGATA and other gamma-ray detectors. The use of such a LH2 target with AGATA and fragmentation beams at GSI was investigated during the PreSPEC campaign [18]. Further details will be discussed in a dedicated TDR.

In Figure 5/c, a schematic diagram of beam line infrastructure and tracking detector positions is represented. Slowing down of the beam to energies suitable for HISPEC experiments will be required. For most of HISPEC experiments using AGATA the beam energy at the target must be reduced to around 150 to 200 MeV/u. The reaction product will be
transported to the subsequent LYCCA detector setup at FLF4. One TPC will be placed before and one XY detector behind the AGATA chamber respectively. The TPC, XY detector and one target DSSSD will be used to track the fragments through the target. In addition, a scintillator will be used to measure the fragment timing. The detectors around the target and the XY detector downstream of the AGATA chamber need to be placed in vacuum. For fragment tracking and identification, the position and timing information at the secondary target will be required. For this purpose, the LYCCA collaboration will arrange two detectors to be placed close to the secondary target position. These are 0.31 mm pixilated Double Sided Silicon Strip Detector (DSSSD) (active area 70 x 70 mm$^2$) for position measurement. The location of the secondary target will be at the center of FLF3 which is 3.455 meters downstream from the previous multiplet (measured from its edge). This leaves enough space for the AGATA/FATIMA setup as well as for additional neutron detectors if necessary for certain experiments.

Figure 5/a. Schematic diagram of FLF3 focal plane detectors for HISPEC experiments (Block sizes not to the scale.).
Figure 5/b. Schematic diagram of the setup with LH2 target and tracking system for HISPEC-200 (Block sizes not to the scale.).

Figure 5/c. Schematic diagram of tracking detector positions and beam tubes needed for HISPEC 200 experiments (detector sizes not to the scale). The dimensions of different tube sections, valves and pumps are shown.

3.3.2 HISPEC-10 experiment

For a certain class of experiments, the beam from the Super-FRS has to be slowed down further to Coulomb barrier energies. This approach allows application of classical reaction types like multiple Coulomb excitation, transfer and fusion reactions for the investigation of nuclei which are too short lived or chemically inert and thus unsuited for ISOL facilities. These
experiments will require an additional degrader in a dedicated chamber at the FLF3 focal plane. The fragments will be first slowed down to a few hundred MeV/u using the degrader at FLF2 and an additional thinner degrader at FLF3 will be used to reduce the energy further to the required energy. The thickness of the degrader has to be remotely adjustable and a Si detector with well-defined thickness has to be inserted in place of the secondary target for calibration purposes.

The degraders will introduce energy and angular straggling strongly reducing the beam quality. Hence, the trajectory of each particle has to be measured after the slowdown. In addition, strong background is generated during the slowdown process, consisting of particles (secondary reaction products, neutrons, high-energy electrons) and radiation (atomic, \( i.e. \) bremsstrahlung and nuclear \( i.e. \) \( \gamma \) decay). Hence, auxiliary detectors will be required for background discrimination via particle identification and/or particle-gamma timing (PGT) determination. A schematic layout is shown in Figure 5/c with all detectors and observables required for an experiment with slowed-down ion beams. The beam identified and tracked by the fragment separator comes from the left. The thickness of the degrader, placed before the chamber will be adjusted to slow down the beam to Coulomb barrier energies at the target position.

The experiments will use a thin target, typically (a few) mg/cm\(^2\) of, \( e.g. \), Au or Al. The target will be surrounded by an array of \( \gamma \)-detectors (\( e.g. \) AGATA detectors). Doppler correction is needed for the \( \gamma \) rays emitted in flight after the thin target. Therefore, the velocity after the target and the interaction point in the target has to be measured via position sensitive thin transmission type detector for each fragment. For determination of the reaction kinematics one also need to know the velocity before and after the target, which will be measured via TOF. After the target a \( \Delta E-E \) telescope will be needed in addition to determine \( Z \) and \( A \) of the outgoing fragment in combination with the measured velocity. All detectors must be placed in vacuum because of the relatively low energy of the slowed down ions.

A scintillator detector at FLF3 will be used after the degrader to distinguish between the surviving slowed-down fragments and contaminants produced in the Al degrader. Secondary fragmentation is expected to happen in the degrader during the slowdown process. Two thin transmission type detectors based on Micro-Channel Plates (MCP) or Secondary Electron Detectors (SED) will be used to track the slowed-down fragments. Details of the available prototype of the tracking detector system are discussed in Section 4.
3.3.2.1 Detector requirements for the HISPEC-10 experiment

The setup will be used to study two-body-reactions of slowed down beams with a secondary thin target positioned at FLF3. Reconstruction of the two-body-kinematics requires knowledge of the incident particle momentum ($P_0$) and the scattering angles ($\theta_1, \theta_2$) of the recoil nuclei. The momentum of the recoil particles ($P_{1,2}$) is given by,

$$P_{1,2} = \frac{P_0 \sin \theta_{1,2}}{\sin(\theta_1 + \theta_2)}$$

(1)

Reconstructing the kinematics of the secondary reaction allows precise identification or...
characterization of reaction channels. The various requirements of the degrader and tracking detector system for these experiments are listed below:

- **Degrader System:**
  Degraders will consist of Aluminum. A thick degrader slows down the beam to a few hundreds of MeV/u and an additional second thinner degrader slows it down to Coulomb barrier energies (a few MeV/u). The thick degrader will be inserted at FLF2. The thin degrader will be directly before the thin window of the chamber at FLF3. Their thickness has to be remotely adjustable.

- **Rate Capability:**
  It has been demonstrated in facilities around the world, e.g. RIKEN [28], that $10^5$ Hz is a reasonable rate for slowed down beam Coulomb excitation experiments. Single nucleon transfer reactions require higher beam intensity, of order of a few times $10^5$ Hz. Due to the spread in energy after the slowing down and observed spiky-ness of the beam at FRS/GSI we expect an average rate of $\sim 10^6$ Hz and a peak rate of $10^7$ Hz for short periods which the detector must be able to handle or at least withstand.

- **Requirement for position resolution:**
  Position resolution of order of $1^\circ$ is sufficient for the nuclear structure studies described above. This was demonstrated in practice with heavy ion reactions around the Coulomb barrier, e.g. with the CHICO [22] particle detector array. The AGATA array allows a chamber size of $\sim 35$cm in diameter. Therefore, a position resolution in the order of mm is required to fulfill the necessary angular reconstruction with $1^\circ$ accuracy.

- **Requirement for energy and time resolution:**
  Most of the experiments will require an unambiguous particle identification of the recoiling nuclei. For the identification, one needs to measure the energy and the TOF of the particle within a few percent of relative error following the equation mentioned here:

$$\left( \frac{\Delta m}{m} \right)^2 = \left( \frac{\Delta E}{E} \right)^2 + \left( \frac{\Delta t}{t} \right)^2 + \left( \frac{2 \cdot \Delta s}{s} \right)^2 = \left( \frac{\Delta E}{E} \right)^2 + \left( \frac{\Delta t}{s \cdot 2m / E} \right)^2 + \left( \frac{2 \cdot \Delta s}{s} \right)^2$$

One needs to separate ions with a mass difference of one nucleon in the region up to $A \sim 130$. Hence $\Delta m/m$ lies in the order of $\sim 0.008$ to $0.025$. This leads to the required resolution of the energy and ToF detectors. It should be noted that the ToF is dependent on the length of the flight trajectory ($s$) and the energy ($E$) of the particles. Due to the slow-down process the energy of the particles is broadly distributed. Hence, it is required that the fastest and heaviest particle of interest can be identified with the given resolution of the detectors. From the equation above one can deduce that the relative error should not exceed 0.8% for $E$, $s$ and $t$ [23]. The time of flight resolution of the system, as shown in Figure 5/d should be in the order of $\sim 150$ ps per meter flight.
path at the Coulomb barrier for a gold target. The interaction point on the target has to be measured within 1 mm spatial uncertainty for a sufficient Doppler correction and for the AGATA γ ray tracking. The ΔE-E telescope must be sufficient to determine Z unambiguously for each particle in a broad energy range from 0.1 MeV/u to 20 MeV/u. The TOF will be measured between a start and a stop detector. The start detector would be mounted behind a vacuum window and the stop detector in front of the secondary target. The combination of both detectors must give the required resolution. The size of both the detectors should be the same. The technology for high resolution ΔE-E telescope has to be developed. If this is not successful, in Coulomb excitation experiments Z will be determined by the detected γ rays for scattering angles below the grazing angle. It is assumed that there will be known γ-rays of interest for the study of Coulomb excitation measurement. For other reactions of interest target like projectile, and light recoiling ion, will be detected in the ΔE-E telescope.

![Required Resolution](image)

**Figure 5/d.** Required TOF resolution (FWHM) for unambiguous mass separation at the Coulomb barrier for interaction with a gold target [23].

### 3.3.3 DESPEC experiment

The core of the DESPEC experiments is the Advanced Implantation Detector Array (AIDA). AIDA has been developed as a stack of three layers of Si detector with a dimension of 8 x 24 cm² and a thickness of 1 mm each. The beam energy needs to be reduced with the help of a degrader at FLF3 so that the beam fragments of interest can be stopped in the AIDA Si detectors. The implanted fragments will undergo α, β, and/or proton decay, which will be also detected by AIDA. Delayed γ-ray decays from the daughter nucleus will be detected by either the DESPEC-Germanium-Array Spectrometer (DEGAS) or other dedicated DESPEC detectors (DTAS, FATIMA) surrounding AIDA. Neutron emission will be detected by either MONSTER or BELEN detectors. A position sensitive TPC and a Scintillator will be placed at FLF3 before AIDA. The scintillator after the degrader will be used to differentiate between
slowed down fragments and secondary fragmentation in the degrader material by means of energy loss correlation of fragments before and after the degrader. In Figure 6, a schematic drawing of the DESPEC setup along with the tracking detectors at FLF3 is shown.

Figure 6. Schematic drawing of the DESPEC setup.
3.3.4 Summary of detector configurations and requirements at FLF3

Table 4 summarises the details of the detectors required at FLF3 for different proposed experimental campaigns of H/D collaboration.

Table 4. Detector and infrastructure requirement at the FLF3 focal plane for H/D experiments including those described in other TDRs.

<table>
<thead>
<tr>
<th>Experiment Code</th>
<th>PSP Code</th>
<th>Detector Component</th>
<th>Length in X (in mm)</th>
<th>Length in Y (in mm)</th>
<th>Length in Z (in mm)</th>
<th>Count Rate (pps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DESPEC</td>
<td>2.4.6.1.3[13]</td>
<td>TPC in air</td>
<td>380</td>
<td>80</td>
<td>450</td>
<td>$&gt;10^5$</td>
</tr>
<tr>
<td></td>
<td>1.2.2.1.1-3</td>
<td>Degrader in air (FRS S4 Degrader modified)</td>
<td>300</td>
<td>80</td>
<td>550</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.2.2.1.1-3</td>
<td>Scintillator</td>
<td>240</td>
<td>80</td>
<td>350</td>
<td>$&gt;10^5$</td>
</tr>
<tr>
<td></td>
<td>1.2.2.13.1-3</td>
<td>AIDA (AIDA TDR)</td>
<td>240</td>
<td>80</td>
<td>2000</td>
<td>$10^3$</td>
</tr>
<tr>
<td></td>
<td>1.2.2.14.1-2</td>
<td>DEGAS (DEGAS TDR) Platform, rails</td>
<td></td>
<td></td>
<td></td>
<td>Out of beam</td>
</tr>
<tr>
<td></td>
<td>1.2.2.17.1-3</td>
<td>DTAS (DTAS TDR) Platform, rails</td>
<td></td>
<td></td>
<td></td>
<td>Out of beam</td>
</tr>
<tr>
<td></td>
<td>1.2.2.3.1-2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.2.2.16.2.1-4</td>
<td>MONSTER (MONSTER TDR)</td>
<td></td>
<td></td>
<td></td>
<td>Out of beam</td>
</tr>
<tr>
<td>HISPEC-200</td>
<td>2.4.6.1.3[13]</td>
<td>TPC in air</td>
<td>380</td>
<td>80</td>
<td>450</td>
<td>$&gt;10^5$</td>
</tr>
<tr>
<td></td>
<td>1.2.2.1.1-3</td>
<td>Scintillator</td>
<td>240</td>
<td>80</td>
<td>350</td>
<td>$&gt;10^5$</td>
</tr>
<tr>
<td>1.2.2.2.1-10</td>
<td>DSSSD</td>
<td>80</td>
<td>80</td>
<td>&gt;10^5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.2.2.2.1-10</td>
<td>Scintillator (CVC diamond)</td>
<td>80</td>
<td>80</td>
<td>&gt;10^5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.2.2.7.1-2</td>
<td>Secondary Target</td>
<td>70</td>
<td>70</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.2.2.3</td>
<td>AGATA (Platform, rails)</td>
<td></td>
<td></td>
<td>Out of beam</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.2.2.3</td>
<td>AGATA-Chamber</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.2.2.15.4</td>
<td>FATIMA</td>
<td>Out of beam</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.2.2.15.10</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.2.2.16.3.1-9</td>
<td>NEDA</td>
<td>Out of beam</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.2.2.1.1-3</td>
<td>XY/time DSSSD/TPC/MWPC</td>
<td>240</td>
<td>&gt; 80</td>
<td>&gt;10^5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.4.6.1.3[13]</td>
<td>TPC in air</td>
<td>380</td>
<td>80</td>
<td>450</td>
<td>&gt;10^5</td>
<td></td>
</tr>
<tr>
<td>1.2.2.1.1-3</td>
<td>Degrader</td>
<td>240</td>
<td>80</td>
<td>550</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.2.2.1.1-3</td>
<td>Scintillator</td>
<td>240</td>
<td>80</td>
<td>350</td>
<td>&gt;10^5</td>
<td></td>
</tr>
<tr>
<td>1.2.2.1.4</td>
<td>MCP/TOF-XY (2 times)</td>
<td></td>
<td></td>
<td>&gt;10^5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.2.2.1.4</td>
<td>SED/TOF-XY (2 times)</td>
<td>400</td>
<td>420</td>
<td>560</td>
<td>&gt;10^5</td>
<td></td>
</tr>
<tr>
<td>1.2.2.2.1-10</td>
<td>Secondary Target</td>
<td>70</td>
<td>70</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.2.2.1.1-3</td>
<td>DSSSD</td>
<td>80</td>
<td>80</td>
<td>&gt;10^5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.2.2.8</td>
<td>AGATA</td>
<td></td>
<td></td>
<td>Out of beam</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

A conceptual drawing of the placement of various tracking detectors in these three experimental setups is shown in Figure 7.
Figure 7. Block diagram of FLF3 focal plane (Block sizes are not to scale).
3.3.4 FLF4 focal plane

The magnetic elements between FLF3 and FLF4 will be used as a magnetic spectrometer for the outgoing reaction channels at the reaction target at FLF3. FLF4 focal plane will host the LYCCA array, which comprises a TOF stop detector and an assembly of ΔE-E detector. A block diagram of the FLF4 focal plane and LYCCA chamber is shown in Figure 8. The design of the LYCCA fragment array will be built as an assembly of a number of ΔE-E detector modules (up to 30). This will be composed of a large-area plastic scintillator detector [2]. The ΔE detectors are 0.31 mm thick square-shaped DSSSD detectors with an active area of 58 x 58 mm. Behind each ΔE detector an array of nine CsI detectors will be used to measure the total energy of the fragments.

If space allows the DESPEC setup can also be placed at FLF4 including AIDA and DEGAS or other DESPEC detectors surrounding the AIDA assembly. Alternatively, modified slow down beam setup can be used here.
3.3.5 FLF6 focal plane

The FLF6 focal plane will be used for implantation and decay spectroscopy measurement of fragments after secondary reaction at FLF3. The DESPEC setup at FLF6 will require ΔE detector, scintillator, XY and an (optional) degrader to assure the identification of the secondary reactions products. There must be the possibility to place a second TPC besides the one already foreseen at FLF6 [11,13]. However, the matter through which the beam is passing has to be kept at an absolute minimum for maximum possible transmission to AIDA. Hence, a TPC or MWPC for XY determination and a scintillator or MCP for timing will be used. A

---

**Figure 8.** Block diagram of FLF4 focal plane and LYCAA chamber (Block sizes are not to scale).
special MUSIC suitable for low-energy particles or another suitable ΔE detector will be used. Alternatively, a modified slowed-down beam setup can also be used here. Figure 9 shows the arrangement of detectors in FLF6. Fast Si will be needed at the end of FLF3 if the energy of the fragment may be too low for TPC (>200 MeV/u) there 3 such detectors would be required. Here also FLF6 ΔE detector could be included.

![Block diagram of FLF6 focal plane (Block sizes are not to scale).](image)

**Figure 9.** Block diagram of FLF6 focal plane (Block sizes are not to scale.).

### 4. The Detector/Instruments Prototypes

As most of the tracking detectors used by H/D are standard Super-FRS detectors, their prototyping is part of the Super-FRS project [11] and it is only referred here for completeness. The specific H/D detector which require prototypes are: FINGER detector, CVC diamond and scintillator (part of LYCCA TDR), microchannel plates (MCP), secondary electron detectors (SED), Target DSSSD and TEGIC MUSIC for DESPEC. The FINGER detector prototyping at GSI and IFJ Krakow is described later in this chapter. Target DSSSD detector was already used as a standard detector for AGATA campaign in 2012-2014. Higher rate capability for this detector is under development at GSI and IUAC, New Delhi.

#### 4.1 Target DSSSD

The Target Double Sided Si Strip Detector (DSSSD) will be mounted as close as possible to the HISPEC-200 secondary target. It will be used to determine the point of interaction of the
heavy ions on the target and for the start of the TOF measurement by the LYCCA array. The XY position measurement will be used to determine the reaction kinematics (via the reconstruction of the incoming and outgoing particle trajectories), and to perform Doppler correction of the detected \( \gamma \) rays. The TOF measurement will be used for identification of the reaction products.

Therefore, the detector should have:

- active area equal to the size of the HISPEC-200 target, 70 x 70 mm\(^2\) or larger.
- X and Y position resolution equal or better than LYCCA and AGATA. A strip pitch of order of 1.5 mm or better is required.
- Timing resolution of the order of FWHM ~ 50 ps.
- Thickness, as small as possible compare to the HISPEC-200 target.
- Life time expectancy longer than an experimental campaign.

The latter requirement suggests a cooled down detector produced from high resistivity silicon. A typical HISPEC-200 target is 400 mg/cm\(^2\) gold. If a 150 \( \mu \)m Si detector is mounted in-front of the target, a \(^{238}\)U ion with energy of 190 MeV/u will deposit 1.0 GeV in the Si detector and 8.2 GeV in the target, leaving the target with energy of 151 MeV/u. The exact detector thickness and strip pitch have to be optimized in order to reach the desired time resolution, taking into account the space available for front-end electronics near the detector. A detector which may be used as a target DSSSD is shown in Figure 10.

![Detector](image)

**Figure 10.** A detector produced by Micron Semiconductors Ltd with active area of 71.63 x 71.63 mm\(^2\) and strip pitch of 0.56 mm. A minimum detector thickness up to 20 \( \mu \)m is available.
The detector electronics should provide energy information for calculation of the weighted position for signal and mirror charge collected at the neighboring strips, but it is not necessary to reach resolution necessary for Z discrimination. The PADI-X ASIC is the latest one in the series of PADI current amplifier/discriminators. It has 8 independent channels providing LVDS logical output signals with their length proportional to the signal amplitude and charge. This so-called Time-over-Threshold (ToT) technique allows measuring the signals charge without using the integrating circuit. The precision of charge measured via ToT is worse than a pure integrator, but it is much faster and sufficient to make weighting of the signals from the neighbor strips. In addition, it can be used to correct the leading-edge timing of the discriminator output signals. The input signals might be optionally split to use an external QDC. The logical output signals are usually split providing a trigger signal to be used for the external logic system. For the best timing, the output signal can be measured by the VME FPGA TDC VFTX2 or its version TAMEX2, developed at GSI. The full chain PADI-X – FPGA TDC has an internal resolution of 10 ps (channel to channel). The channel ID will be recorded, providing the DSSSD strip number, and the time-stamp mechanism allows the synchronization with external systems.

The PADI-X board might be integrated into the TAMEX2 system and placed outside of the vacuum or installed separately, on the same PCB where the detectors are mounted. In the first case each strip will be connected to the front-end via high quality coaxial cable, the second case – all LVDS signals from the discriminator will be connected via flat cables. Depending upon the performance the one of the solution will be adopted.

4.2 The FINGER detector prototypes

Since 2010, the NUSTAR collaboration has been using a prototype of the FINGER detector as the start TOF tracking detector for the PreSPEC experiments. The capabilities of this detector have been demonstrated in different experiments and expertise has been gained in its design and operation [23]. For the TOF measurements at a high rate an upgrade of the FINGER detector is being considered. The new version of the detector is proposed to be placed at the FMF2 focal plane of the Super-FRS.

The FINGER detector is composed of strips of fast plastic scintillator read-out in pairs at both ends by Photomultiplier Tubes (PMTs). In 2010 a prototype FINGER detector, consisting of 15 plastic strips, each being 14 mm wide and 1 mm in thickness, was commissioned [12]. The consecutive version of the FINGER detector was developed with 51 strips, each having a dimension of 4.4 mm in wide and 1 mm thickness. This detector was successfully used in experiments of the PreSPEC-AGATA campaign in 2014 [21]. For both campaigns the time and energy loss information were obtained from the detector prototypes. Thanks to the intrinsic segmentation, the detectors were also capable of providing position information with a resolution given by the strip size.
4.2.1 Summary of prototype results

The prototype of the FINGER detector was tested from February to April 2014 as part of the PreSPEC-AGATA setup at GSI [24] at the S2 focal plane. Each pair of strips was glued to a bended UV-transparent PMMA light guide using a two-component silicon glue. The light guides were optically coupled to Hamamatsu R9880U-01 photomultiplier tubes (PMTs) using silicon pads. 13 power supplies were used to power the PMTs, each one powering up 4 tubes. Independent potentiometers were added to the setup to allow independent adjustment of the voltages. The PMTs were read-out using the LANDFEE discriminator [25], which allowed the determination of the leading and trailing edges of the incoming PMT pulses. The timing information was recorded using two CAEN V1290 Multihit TDCs. TRIPLEX cards [25] were used for the remote control of the thresholds and to obtain the monitoring signals. One of the TRIPLEX cards was connected to a network module to make the system remote controllable via Ethernet by a lab-view program.

Time and Time-over-Threshold (ToT) spectra were obtained for Fe and Ni beams with different incoming intensities. The efficiency of the FINGER detector prototype was on average 2% lower than the one of the standard scintillator at S2, mainly because of gaps between the strips. Figure 11/a shows a typical ToT spectrum recorded in one of the PMTs. Using these spectra it was possible to decide which strip had the higher charge collection and therefore which was the strip that was hit. Position and timing information from that strip were used for each event and a preliminary analysis was performed. Figure 11/b shows the correlation between the strip selected as being hit and the position determined by the standard Time Projection Chambers (TPCs) which has a position resolution of the order of 1 mm. In spite of the clear correlation, some background was also present. This background could be identified as coming from two different sources: The high fragment rate present as S2, which reduced the performance of the TPCs and the possibility of correction for having two particles hitting the FINGER detector during the same trigger, which can lead to a wrong strip selection.
To study these effects, the number of PMTs fired per event was calculated. When all fired PMTs were adjacent they were considered as coming from a single particle interaction due to the possible optical crosstalk. Otherwise, it was considered that a second particle produced the signals. The number of these sets of adjacent PMTs was called cluster multiplicity. Figure 12/a shows the number of clusters recorded versus the number of PMTs fired. It can be seen that for the case of a single particle, the most likely case is to have two PMTs fired, corresponding to one strip.
Figure 12. Results obtained for the identification with the prototype detector

The remaining events could be properly reconstructed in a more detailed analysis. Using the timing information from a given strip, the ToF between the FINGER detector and the S4 scintillator, placed in the last focal point of FRS, was calculated. Figure 12/b shows the ToF versus the atomic number of the particles obtained from the MUSIC ionization chambers. This plot presents a preliminary identification plot and shows the feasibility to use a segmented plastic detector as ToF solution for the FMF2 focal plane of the Super-FRS.

4.3 Prototype position sensitive TOF detectors for slow down beam experiments (HISPEC-10)

There are three possible detector technologies which may meet the requirements for the position sensitive TOF detectors for HISPEC-10. The detectors are in R&D stage. A decision on the final detector technology which will be used will be made based on the prototypes performance.

4.3.1 MCP based solution

Transparent beam tracking detectors based on microchannel plates (MCP) are proposed for the measurement of the ion trajectories before the target for slowed-down beams. This measurement also includes the measurement of the velocity and the interaction point inside the target which can be deduced by extrapolating the trajectory. Two separate detector units will be used for the measurement. Both are capable to measure the time of the passage of an ion
and the position of the passage. When an ion passes through a thin foil e.g. carbon (40 µg/cm²) or metalized Mylar, secondary electrons are emitted at the position of the passage. These electrons are imaged by an electrostatic system on an MCP, where the electrons are multiplied. The position of the produced electron avalanche is measured via a dual delay line (DDL). The detectors insert as less as possible material in the way of the beam as possible to reduce additional energy straggling. One of the units has to be placed right in front of the target to get the most accurate position measurement for the interaction point and for PGT.

There are two configurations possible for these detectors. One uses a 45° tilted electrostatic mirror while the other one uses a 45° tilted foil and magnetic field to guide the secondary electrons to the MCP. Each unit has an optical transparency of about 73% (79% for the type with the magnetic field) due to the micro meshes used for the electrostatic imaging system.

At the current status of development two sizes of detector heads (MCP+DDL) are available. Two rectangular types with a size of 60 x 40 mm² or 100 x 70 mm² and a round type with a diameter of 150 mm. There is an ongoing development to reach the required time and position resolution. The detector heads alone show a spatial resolution below 1 mm. The configuration with an electrostatic mirror was extensively tested [26]. Currently a time resolution (FWHM) of ~ 600 ps and a position resolution of ~ 13 mm could be reached with the larger detector. The version with the magnetic field appears to be a promising way to overcome the problems with spatial resolution [26]. This detector is also capable to track 100 MeV/u nucleons as entrance detector for a spectrometer. It can be installed at the entrance of a spectrometer for HISPEC-200 experiments, allowing to substitute a TPC to reduce energy straggling. Two alternatives are under discussion for the measurement of the trajectory before the target. One is a DemiSeD (mini prototype of Secondary electron Detector) [27], and the other one is MWPC [26]. The working principle of DemiSeD is comparable to the described MCP based detector with magnetic field and described below. Therefore, the electron transport from the DemiSeD and the detector heads with MCP can be combined to reach the required time and spatial resolution.

**Figure 13(a):** MCP based transparent beam tracking detectors. These versions are without magnetic field. Sensitive size is 70 x 100 mm² (left) and Ø160 mm (right).
4.3.2 DemiSED based solution

Low-pressure gaseous detectors for beam tracking and ToF measurements are another alternative. Several mini prototypes based on the SED principle [27] were constructed and tested [29, 30]. The working principle is similar to the MCP. A very thin emissive foil made of 0.9 μm thickness aluminized mylar is placed in beam at 45° with respect to the beam line. When the heavy ion beam passes through it secondary electrons are ejected. Since the mylar foil is polarized at -10 kV these electrons are accelerated and focused using electric and magnetic fields towards the detector, which is located out of beam at a distance of 20 cm. Two copper coils are used to apply the magnetic field that is necessary to focus the electrons at the entrance window of the detector.

The best results in terms of time resolution (around 200 ps FWHM) and spatial resolution (1 mm FWHM) was obtained with the 2D-MiniSED prototype (70x70 mm2 active area). A larger-size detector prototype was constructed and also tested in the laboratory with a $^{252}$Cf source, DemiSED.

![Figure 13(b): A real size SED detector coupled to an emissive foil.](image)

The active area of DemiSED is 120x200 mm2. The anode wires of 20 μm diameter gold-plated tungsten are placed in the center of a 3.2 mm gap, which is filled with pure isobutane at 6 mb. A single pixellated cathode plane is placed at 1.6 mm from the anode. It is made from a PCB (printed circuit board) with 67 (X) + 47 (Y) cathode strips of 3 mm pitch (see figure 13(b)). The detector window is made of a 0.9 μm aluminized mylar foil. Inside the detector no dead areas exists without electric field. The anode is polarized at around 600 V. The spatial resolution of DemiSED was measured as 1 mm (FWHM), with a time resolution of 280 (FWHM) and a rate capability of $10^6$ pps. It was also demonstrated that the magnetic field is mandatory to get a good spatial resolution [31]. For that reason the detector is located between the coils as it is shown in the Figure 13(c).
4.3.3 Multi-Wire Proportional Counters (MWPC) based solution

Alternatively, it is proposed to develop TOF system based on two MWPCs for tracking slowed-down projectile fragmentation beams from the Super-FRS. It will provide event-by-event beam tracking capabilities to generate information on the beam profile in terms of its trajectory, mass and energy of the secondary species using position and TOF information. For the envisaged characterization of the slowed-down fragments, transmission-type beam-tracking detectors with a time resolution of $\sim 100$ ps for each unit, a position resolution of $\sim 1$ mm (in both dimensions) and a high count-rate capability of $\geq 1$ MHz are needed. They should have a large geometrical efficiency and introduce minimum straggling to the ions. MWPC-based beam tracking detectors provide a cost effective and flexible solution for the measurement of ion trajectories, beam profile and velocity spread. They can be designed in any size and geometry depending upon the experimental requirements. Moreover, they are not prone to radiation damage and are operated at low working voltages of typically 500-600 V. Conventionally, they are designed in a three-electrode geometry having a central cathode sandwiched between two anode frames for position determination. The cathode is prepared from a mylar foil, aluminized on both sides, with a typical thickness of 2 µm. The anode wire frames are prepared from gold-plated tungsten wires of diameter 10-20 µm. All electrodes are prepared on commercially available printed circuit boards. They are generally housed inside an aluminium frame and operated with Isobutane gas at typical operating pressures of 3-5 Torr. Mylar foils of thickness 0.5 – 0.9 µm are used for isolating the gas from the beamline vacuum ($10^{-6}$ Torr). An MWPC with active area 150 x 100 mm² can be easily housed in a 250 mm diameter beam tube. The maximum areal thickness of a MWPC is 500 µg/cm² with a geometrical transmission efficiency of about 85 – 90 %. This thickness can be reduced to 300 µg/cm², if the cathode foil is replaced by a wire frame. For two such MWPCs with a total geometrical transmission
efficiency of 80 %, the thickness will be less than \(-1 \, \text{mg/cm}^2\) or effectively a polypropylene foil of only 10 \(\mu\text{m}\) thickness. A time resolution of 100 ps and position resolution of 1 mm are achievable with 10 \(\times\) 10 cm MWPC with a central cathode foil. The position information is extracted using the delay-line technique by interconnecting wires with an inductor-capacitor filter. In this was a total of 5 readouts will be present: one cathode used for the master timing and 4 positions (X-left, X-right, Y-up, Y-down). As the isobutene gas needs to be circulated continuously in the detector, a rotary pump is required at the output stage of the gas handling system. An additional rotary pump is required for slow pumping of the chamber during initial stages of evacuation. To protect the fragile Mylar foils and wire frames precision needle valves are required while evacuating as well as venting. The gas pressures inside the MWPC will be also controlled by needle valves. A dial gauge sensor (0 – 25 mbar) is required for measuring precisely the pressure inside the MWPC. In Figure 14, the proposed design and implementation of a MWPC for fission-fragment measurements is schematically shown. Expected intrinsic time resolution is 100 ps. For two MWPCs, a geometrical transmission efficiency of \(~88 \%\) for 20 \(\mu\text{m}\) and \(~93.5\%\) for 10 \(\mu\text{m}\) wires, respectively, will be reached, while introducing a total of 1 \(\text{mg/cm}^2\) thickness (Mylar equivalent) into the beam path. For heavy ions detection efficiency close to 100% is expected. To further minimize straggling, the cathode foil could be replaced by a wire frame. For improved timing and faster charge collection, the wire pitch has to be reduced to \(~300 \mu\text{m}\). The aerial thickness of the MWPC can be further reduced by using multi-step counters with a four-electrode configuration as shown in Figure 14(f). In this case all electrodes are wire frames with 635 \(\mu\text{m}\) wire pitch and an active thickness of less than 200 \(\mu\text{g/cm}^2\). Multistep counters (cf. Figure. 14(f)) have higher gains (by a factor of 50) and can be operated at lower pressures of 3 Torr. However, their timing properties are inferior compared to MWPC with a three-electrode geometry. A time resolution about 200 ps is achievable with such counters. Their geometrical transmission is also reduced, i.e., to 88% and 78% for one and two detectors, respectively.
Figure 14. (a) Schematic view of the MWPC solution, (b) circuit diagram for the delay line, (c) delay line example, (d) example assembly for fission fragment detection, (e) example of a cathode signal for a Si beam at 3 torr isobutene and (f) schematic design of a multistep-MWPC design.
5. Simulation

The fragment production and identification process in Super-FRS has been simulated using LISE++ [32] and MOCADI [33] software framework considering specific and essential features for H/D experiments. The main goal for the simulation has been to optimize the yield, energy and distribution of the fragment of interest at the focal planes where the subsequent decay or excitation will be studied. The observed yield at the final focal plane will depend upon the production rate and transmission of the fragments through the fragment separator. The thickness of different degraders has to be decided to obtain the optimized transmission and separation in different focal planes. Apart from yield, the selectivity and sensitivity are crucial parameters to study very rare nuclei. The primary beam (e.g. $^{238}$U) at energy 1.5 GeV/u is used for production of heavy fragment (A~200) at the target.

5.1 Charge state contribution of fragments:

From the production to implantation/reaction the fragments will be required to be transported through several g/cm$^2$ of matter for the H/D experiment leading to considerable probability of acquiring various charge states. To equilibrate the charge state distribution and further ionize the non-fully stripped fragments an Nb stripper is used directly after the production target and at different focal planes. The in-flight separation of fragments will be achieved using two degraders at the focal planes FPF2 and FMF2. An achromatic degrader will be used in the FPF2 and further separation of fragments will be carried out with a second degrader at FMF2. However, the population from non-fully ionized charge states will increase as the ions pass through matter and loose energy. The contribution of non-fully stripped charge states is higher for heavier fragments since electron capture is more probable at lower energy. The target thickness in the simulations has been adjusted for maximum production of the primary fragment by optimizing transmission losses, while the minimum stripper thickness for which charge state equilibrium can be reached has been chosen in the simulation (obtained from calculations with the code GLOBAL [34]). The stripper thickness will needed no be greater than the thickness required for attaining the equilibrium charge state distribution. The minimum thickness requirement is calculated in the simulation by considering layers of matters with thicknesses sufficient to avoid pre-equilibrium description of charge states. The charge state distribution that has been used for the MOCADI simulation is calculated after the beam has passed the first stripper and not individually for each layer of matter. Further simulations have been performed to estimate the charge-state contributions (other than the fully ionized fragments) at different stages of the Super-FRS. As an example, for $^{100}$Sn these contribute with $\sim 2\%$ (up to the MUSIC detector at FLF2).

For heavy fragments (A ~ 200) a significant contribution from lower charge states is observed.
(~ 20%). However, if the beam energy is kept above 400 MeV/u before the MUSIC detector the non-fully stripped contribution remains ~ 2% for medium heavy fragments (A ~ 100). This effectively guarantees the correct Z identification for the isotope of interest in the MUSIC detector. However, for heavy fragments (like 214Pb) the contribution of charge states can be as big as 20%. This increase can inherit some additional problems, such as transmission loss in the next magnetic stages as a result of acquiring electrons.

The charge-state distribution of the fragments has been simulated at FLF2 and FLF3. A combined measurement of the position at FLF2 (or FLF3) and PID at FMF2-FLF2 will ensure clean separation of isotopes also for heavier masses (A > 200). The position of different charge states at FLF2 and FLF3 will be mirrored with respect to the central fully stripped fragment. However, the fragments with non-fully stripped charge states will be more widely distributed on the implantation detector. This spread in position is problematic if the size of the detector at FLF3 is not adequate. However, according to LISE++ simulations the 7 cm wide AGATA target will be adequate for charge-state collection of the primary fragment. In addition, AIDA with a total width of 24 cm will have a sufficiently large acceptance angle compared to the spread of fully-ionized primary fragments. AIDA can thus also be used for implantation and decay studies of non-fully ionized charge states of the primary fragment and the nearby isotopes with small difference in A/Q.

The degrader thickness at FLF2 and FLF3 can be adjusted to have optimum transmission, sufficient energy loss to achieve a correct implantation and minimum transmission of secondary particles which can disturb the down-stream γ detectors. For example, the degrader thickness at FLF2 can be reduced and the energy loss required for implantation can be obtained by the FLF3 degrader. This will keep the beam focused at FLF3, and the final slowdown will be done near the secondary target/implantation detectors. However, from the experience of FRS experiments at GSI we know that a “FLASH” [35] of secondary particles (bremsstrahlung γ rays, protons, other low-energy charged particles) will be produced with high intensity in the final degrader which will saturate the HPGe detectors. The FLASH will be observed within the prompt time window (< 50 ns) in the timing spectrum of the HPGe detectors. These background events do not pose a significant challenge to the DESPEC experiment, where β-delayed γ rays will be the main interest for investigation. The preceding β-decay at AIDA can be used to follow up the γ-decay events in the daughter nucleus. This is one of the reasons for different degrader configurations that has been suggested for HISPEC and DESPEC experiments.

For DESPEC an additional degrader is suggested at FLF3, which can be used to compensate for the energy loss required for implantation in AIDA, while the FLF2 degrader can be made thinner or completely removed. For HISPEC it is advisable not to use a degrader at FLF3, but to use instead a thicker degrader at FLF2. While this would worsen the transmission, the event-by-event charge-state selection in the MUSIC will be achieved and thus not pose any ambiguity in Z identification for most experiments.

Another possible consequence of the fully stripped ions acquiring an electron can appear for certain decay spectroscopy experiments where long-lived isomeric states are observed. The γ-decay from the long-lived isomeric states can compete with β-decays. The β-decay half-life
can become shorter through electron capture. However, these special experimental cases can be treated separately. The simulated distribution of $^{214}$Pb (red), $^{214}$Tl (green) and $^{214}$Bi (blue) fragments in the focal plane at FLF2 is shown in Figure 15. The fully ionized and the H-like charge-state of each fragment are focused at separate positions. While there is overlap between the different charge states they can be differentiated by $A/Q$ and $Z$ identification as described in section 5.5.

![Figure 15. Simulated distribution of $^{214}$Pb (red), $^{214}$Tl (green) and $^{214}$Bi (blue) fragments at the FLF2 focal plane in achromatic mode are shown (details of the simulation can be found in the simulation section of the text). Two different charge states are localized at different positions at the FLF2 focal plane.](image)

### 5.2 Secondary Fragmentation:

Secondary fragmentation in the various matters that the fragments are passing is an important factor in calculating the final yields. The effect of secondary fragmentation in matter is found to be much higher for the production of medium mass ($A \sim 100$) fragments. For these fragments the contribution of secondary fragments in the total yield increases with thickness. For heavy fragments ($A > 200$) the optimum yield of the secondary fragments peaks around the same matter thickness as primary fragments. Additional secondary fragments may also be contributed from the matter used for slowdown, tracking and identification of fragments. Complexity may arise to identify the secondary fragments produced in the matter present at FLF2 and FLF3. These secondary fragments, produced from primary fragments will lead to contaminations since they were falsely identified in $Z$ and $A$ before FLF2. These contaminations can be removed by a correlation of the energy loss spectrum before and after the degrader measured in the TPCs placed at FLF2 and FLF3.
5.3 Rate estimation accuracy:

It was noticed that there exists inconsistency between calculations performed with LISE and MOCADI in terms of the position distribution of the fragments in the focal planes. In order to maintain consistency, all simulations have been performed also in MOCADI. Only the slits in dispersive plane (X) were adjusted in the simulation. However, since the values of these slits are taken from LISE, the final rates of non-central fragments are only approximate.

5.4 Achromatic and Monochromatic settings:

Depending upon different experimental requirements, i.e. Achromatic or Monochromatic mode of the Super-FRS, different degrader angles will be used at the FMF2 focal plane. The degrader angle corresponding to the experimental requirement is calculated using the WEDGE program. In achromatic mode the fragments incident at various positions onto the degrader should be focused at FLF2. In Figure (16/a) the correlation between angle and position at FMF2 and FLF2 is plotted. In Figure (16/b) the correlation between the positions at FMF2 and FLF2 is plotted for achromatic settings.

![Figure 16](image)

*Figure 16. (a) Calculated angle of fragments at FMF2 vs. their position at FLF2 and (b) calculated position at FMF2 vs position at FLF2 is plotted*

Simulations have been carried out with $^{124}$Xe and $^{238}$U beams for the production of medium (A~100) and heavy (A >200) primary fragments, respectively.
5.5 Fragment identification using $B\rho$-$\Delta E$-TOF method:

The Super-FRS tracking detectors provide unambiguous event-by-event identification of the primary fragments. The charge $Z$ and mass number $A$ will be identified using $B\rho$-$\Delta E$-TOF method.

The experimental conditions for particle identification are implemented in the MOCADI simulation. A pair of TPCs, both at the FMF2 and FLF2, has been used for position and angle measurements. The simulated energy loss in the MUSIC detector has been used for the $\Delta E$ measurement to identify the $Z$ of the fragment. Finally, the PID is derived from the simulated data using the following equations:

$$TOF = \frac{L}{\beta c} \quad (3)$$

$$A = \frac{B\rho \ c}{\beta \gamma m_u} \quad (4)$$

The velocity of the fragments ($\beta$) is obtained by equation (3) using a TOF measurement obtained from the time stamps from the start and stop plastic scintillator detectors at FMF2 and FLF2. A correction for the additional path length travelled by the non-central fragments is obtained by incorporating the position and angle information at the focal planes. The global transfer matrix elements from FMF2 to FLF2 are used for this purpose. The $B\rho$ value of the central trajectory ($B\rho_0$) is obtained from MOCADI, while ATIMA is used for the energy loss, the energy and angular straggling in matter (e.g., Tracking detectors, Degraders etc.). The $B\rho$ values for non-central fragments are calculated from the central fragment using the following relation:

$$B\rho = B\rho_0 \cdot (1 + \frac{X_{FLF2} - M \cdot X_{FMF2}}{D}) \quad (5)$$

where $M$ and $D$ are the magnification and dispersion between FMF2 and FLF2, respectively. The positions $X_{FLF2}$ and $X_{FMF2}$ are obtained event by event from the TPCs at the respective focal planes. The magnification and dispersion properties of this section of the Super-FRS is used for this purpose.

Several examples have been considered for the simulation of the separation and identification of fragments using the tracking detectors at FMF2 and FLF2. The present TPCs have limited performance at very high count rates. This will require alternative solutions for the position
determination at FMF2. The simulations for the A/Q determination have been carried out using either a position measurement from the FINGER detector or from the TPCs, thereby considering the possibility of high intensities (> 10^5 pps) at FMF2 for some experiments. The FINGER detector is capable to withstand higher rates, but will provide a position uncertainty of ~4.5 mm in the dispersive plane, while the TPCs will allow for a position resolution of 1 mm. The position correction due to the incident angle is done from the twin TPCs at FLF2, where the count rate will be low enough to operate them. The results of the simulation show overall good A/Q separation for medium as well as heavy mass fragments.

The realistic equilibrium charge state distribution of the ions transported through the different parts of the Low-Energy Buncher (LEB) at the end of the Super-FRS is incorporated from the GLOBAL code to simulate the equilibrium charge state distribution after matter at the corresponding beam energies. To ascertain that the equilibrium charge state is attained, additional Nb strippers are placed at FPF2, FMF2 and at FLF2 in the simulation. Additional complexity arises for separating the charge-state partners and the nearest neighbor isotopes. The problem is more pronounced for heavier isotopes where A/Q resolution is less.

A typical case is presented here for separating ^{214}Pb, ^{214}Tl and ^{214}Bi fragments produced from a ^{238}U beam on a C target at an incident energy of 1.5 GeV/u. The ion optics has been optimized for separating ^{214}Pb as the central fragment along the different stages of the Super-FRS. Achromatic focusing of the fragments at FLF2 is ensured by adjusting the thickness and angle of the degrader at FMF2. At each stage of the separator the magnetic field is determined from the \( B_\rho \) value corresponding to the central fragment. In Figure 17/a, the simulated A/Q plot for ^{214}Pb (red), ^{214}Tl (green) and ^{214}Bi (blue) is shown. Only the fully stripped and hydrogen-like (i.e. one electron in the K-shell) charge state distributions of the fragments have been considered. As shown in Figure 17, the hydrogen-like charge state of ^{214}Pb (red) has the same A/Q as the fully stripped ^{214}Tl (green) while the hydrogen-like charge state of ^{214}Bi (blue) is overlapping with fully stripped ^{214}Pb. The H-like (^A Z) fragment and the fully ionised (^A Z-1) fragment will have similar B_\rho and \( \beta \). Interestingly, some of these H-like (^A Z) fragment get one electron removed within the Nb separator of the MUSIC detector at FLF2. To separate these fragments from the fully ionised (^A Z-1) fragments the Max( Z1, Z2) is determined within the two sections of the MUSIC detector for each fragments and this value is considered as the Z of the fragment. This however separates only a certain fraction of the overlapping fragments as shown in the Z vs A/Q plot of the Figure. 17/b. The fragments with Z = 83, 82 and 81 are identified in two distinguishable regions of same Z and different A/Q. The fragments which do not change their charge state cannot be separated with this technique (the overlapping blue-red and red-green regions). These fragments could be further separated from their position at FLF2. In Figure 17/c, the position at FLF2 and A/Q for fragments identified as Z = 82 are plotted. The previously overlapping blue-red region is now clearly separated from their position at FLF2. The separation of the isobaric analogue fragments is not so good in the monochromatic settings.
Figure 17. (a) Simulated A/Q distributions for $^{214}$Pb (red), $^{214}$Tl (green) and $^{214}$Bi (blue) fragments using position determination at FMF2 from the FINGER detector. (b) Simulated Z vs A/Q distributions for the same isotopes. See text for explanation how to separate these fragments.

Figure 17(c). A/Q vs. FLF2 position correlation for the events, represented in the Z vs A/Q plot shown in figure 17 applying an additional Z discrimination between Z=81.5 and Z=82.5. The overlapping $^{214}$Pb and $^{214}$Bi fragments (blue-red region in figure 17(b)) are now clearly separated from the H-like charge state. The fragments are represented with same color as in figure 17(b).
5.6 Simulation of the FINGER detector:

5.6.1 MOCADI simulation

Simulations were performed for the intermediate focal plane FMF2. A \(^{238}\)U beam at 1.5 GeV/\(u\) impinging on a C target of 2.5 g/cm\(^2\) was considered as a representative example. The Super-FRS was set to select \(^{132}\)Sn as isotope of interest. It was found that the energy of the beam 150 cm after the degrader was 1000 MeV/\(u\). Figures 18/a and 18/b shows the spatial distributions in the x and y planes of the \(^{132}\)Sn isotopes at FMF2. The proposed size of the detector, is clearly enough to cover the full focal plane area.

Figure 18. Simulated special distribution for \(^{132}\)Sn ions at FMF2 (included from Ref.[13].).

5.6.2 Geant4 simulations

A dedicated Geant4 simulation was developed to optimize the design of the optical components of the detector. The simulation included all the physical processes relevant for the interaction of heavy ions with a plastic scintillator. In particular, the creation and propagation of optical photons inside the scintillator was included. A simplified photomultiplier tube (PMT) model was also simulated. The simulation was used to determine the amount of optical cross talk between the plastic strips and the light guides. If both the light guides and the strips of plastic scintillator are perfectly reflective, only photons above the critical angle can escape the optical element and have the possibility to be detected in a different PMT. Under this assumption the average number of responding PMTs is 3, which does not reproduce the experimental
observation. If surfaces with different roughness are used in the simulation, it is possible to produce a cross talk that with up to 15 PMTs responding, which is consistent with the values obtained for the FINGER detector prototype. This indicates that although the optical components are carefully prepared, some degree of cross talk will be present. This can be improved with the use of a reflective material between the optical components. Simulations of different types of reflective coatings showed that the use of a diffuse reflective layer should be preferred over a specular reflector in order to collect the highest number of optical photons.

5.7 Simulation for slow down beam setup:

The system of degraders used for the slowed down beam experiment will introduce additional energy and angular straggling to the beam at FLF3. Simulations with MOCADI were carried out to estimate the beam-spot size and the energy distribution after the slowdown process. The simulated $^{214}$Pb fragments, from fragmentation of $^{238}$U beam on the primary target, were separated in achromatic–monochromatic mode (in the pre- and main separator, respectively). The beam spot and energy distribution at FLF3 after the slow down process are shown in Figures 19/a and 19/b respectively. The simulation shows the beam will be as wide as 20 cm in the dispersive plane after the slowdown at FLF3 for an energy distribution from 0 to ~20 MeV/u.

Figure 19. MOCADI simulation for $^{214}$Pb fragments, produced in $^{238}$U fragmentation at 1.5 GeV/u, and slowed down in two steps to a mean value of ~10 MeV/u at FLF3 (target location for the HISPEC10 experiments) with the Super-FRS set to achromatic mode in the pre-separator and to monochromatic mode in the main separator. The X-Y and energy distributions are shown in panel (a) and (b,) respectively.
6. Technical specification and design details

The infrastructure elements necessary to run the H/D experiment are summarized in Table 5.

**Table 5. Infrastructure elements for H/D experiments along with dimension details.**

<table>
<thead>
<tr>
<th>Element</th>
<th>Work package/ PSP code</th>
<th>Comments</th>
<th>Dimensions (mm) /INFO</th>
</tr>
</thead>
<tbody>
<tr>
<td>FINGER detector at FMF2</td>
<td>1.2.2.1</td>
<td>Described in this TDR</td>
<td>380 x &gt;100 Drive</td>
</tr>
<tr>
<td>FINGER detector at FLF2</td>
<td>1.2.2.1</td>
<td>Described in this TDR</td>
<td>&gt;240 x 100</td>
</tr>
<tr>
<td>Scintillator at FLF2 in vacuum</td>
<td>1.2.2.1</td>
<td>Standard Super-FRS</td>
<td>380 x 100 Drive</td>
</tr>
<tr>
<td>Degrader modification</td>
<td>1.2.2.2</td>
<td>S4 degrader enlarged</td>
<td>250 x 100 Drive</td>
</tr>
<tr>
<td>FLF3 beam line tubes, pumps</td>
<td>1.2.2.2</td>
<td>Described in this TDR</td>
<td>Chambers, tubes + adapters from CF 400 to CF200, Pumps, and infrastructure</td>
</tr>
<tr>
<td>Scintillator at FLF3 in air</td>
<td>1.2.2.1</td>
<td>To be adopted from Super-FRS Design</td>
<td>240 x 100 Support</td>
</tr>
<tr>
<td>DSSSD/SED end of FLF3 Same as TA-DSSSD x3</td>
<td>1.2.2.1</td>
<td>Described in this TDR</td>
<td>240 x 80</td>
</tr>
<tr>
<td>FLF4 beam line tubes, pumps</td>
<td>1.2.2.2</td>
<td>Described in this TDR</td>
<td>Adapter to LYCCA chamber and infrastructure</td>
</tr>
<tr>
<td>Platform/Component</td>
<td>Section</td>
<td>Description</td>
<td>Additional Notes</td>
</tr>
<tr>
<td>------------------------------------</td>
<td>----------</td>
<td>-------------</td>
<td>------------------</td>
</tr>
<tr>
<td>Platforms, rails DESPEC</td>
<td>1.2.2.3</td>
<td>Described in this TDR</td>
<td></td>
</tr>
<tr>
<td>Platforms, rails HISPEC</td>
<td>1.2.2.3</td>
<td>Described in this TDR</td>
<td></td>
</tr>
<tr>
<td>MCP/SED detectors SDB</td>
<td>1.2.2.1</td>
<td>Described in this TDR</td>
<td>200x120</td>
</tr>
<tr>
<td>TA-DSSSD</td>
<td>1.2.2.1</td>
<td>Described in this TDR</td>
<td>80x80</td>
</tr>
<tr>
<td>Platform FLF4</td>
<td>1.2.2.3</td>
<td>Described in this TDR</td>
<td></td>
</tr>
<tr>
<td>MUSIC/ΔE at FLF6</td>
<td>1.2.2.1</td>
<td>Super-FRS design or new</td>
<td>240x80</td>
</tr>
<tr>
<td>Scintillator at FLF6 x2</td>
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<td>To be adopted from Super-FRS Design</td>
<td>240x100</td>
</tr>
<tr>
<td>Cabling</td>
<td>1.2.2.6</td>
<td>Described in this TDR</td>
<td></td>
</tr>
<tr>
<td>Safety</td>
<td>1.2.2.5</td>
<td>Described in this TDR</td>
<td></td>
</tr>
</tbody>
</table>
6.1 Specification of the FINGER detector and prototype implementation

6.1.1 Optical components

The strips of the FINGER detector will be made of BC-420 plastic scintillator from St. Gobain. This material has been reliably tested in the previous two versions and shows one of the best time responses achievable with 0.5 ns rise time and 1.5 ns decay time. The refractive index of this material is 1.58 and its wavelength of maximum emission is 391 nm. A possible improvement on the timing properties of the detector is to use the BC-422Q, which has a rise time as low as 100 ps and a decay time of 0.7 ns. For this type of plastic, the maximum light emission is at around 375 nm. Based on MOCADI simulations, the width of the strips is recommended to be 4.5 mm. Due to the fact that the window of the PMT foreseen to use is 9 mm, a width of 4.4 mm is considered optimal. This number can vary if a different PMT is available in the market at the time of construction. The length of each strip will be 200 mm, in order to comply with the size requirements at FMF2. The thickness of the strips can be changed between 1 and 3 mm. The 1 mm strips can be used to measure most mid-mass isotopes, while the 3 mm strips should be used when the energy of the ions is too high, or its charge too low and an increased energy loss is desirable. The coupling between the plastic strips and the PMTs will be made using bent PMMA light guides, as was tested for the prototype FINGER detector. The experience gained with the prototype also indicated that these pieces must be machined and polished to guarantee a proper fitting in the mechanical structure. The material for the light guides will be UV-transparent plexiglas (GS2458), which has about 90% transmission for light between 300 and 850 nm. The refractive index of this material is around 1.49. Although it is slightly different than the refractive index of the plastic scintillator, it is the only material available with high transmission in the energy range we are interested in. The plastic strips will be coupled to the light guides using two-component silicon glue. This allows an easy dismount of the strips in case it is needed. In order to reduce the cross-talk, both the strips and the light guides will be covered by commercial diffuse reflective painting. Nevertheless, to avoid an unnecessary increase of the dead layer between the strips, a single layer of painting is recommended. For the light guides, the presence of a thicker layer of painting is advisable. The set of strips glued to light guides will be mounted in an independent frame which can be easily mounted in the rest of the structure. This fulfills the versatility requirement of the detector. It is foreseen to have spare frames of 1 and 3 mm strips ready to be changed during beam time.
Figure 20: Optical components used for the prototype detector.

This mounting allows a clear identification of the strip that was hit, while at the same time it reduces by half the amount of PMTs needed if one would read each strip at both ends with single PMTs. For the optical coupling between the light guides and the PMTs, silicon pads will be used. No permanent glue is recommended for this coupling to allow for a quick exchange of the different frames. The PMTs which have been used for the prototype and that are recommended are Hamamatsu R9880U-01. These PMTs have a typical response type of 2.7 ns, which makes them suitable for timing purposes. The wavelengths which the PMT can detect range from 230 to 920 nm, with a peak in quantum efficiency at 630 nm. The voltage needed to power this detector is between 900-1200 V.

Figure 21. Assembly of the light guides and the PMTs.
Figure 21/a shows the way the bent light guides were placed in the mechanical structure for the prototype detector. As shown before, two plastic strips were mounted in one of the ends of the light guide, while at the other end the PMT was attached. Figure 21/b shows the final mounting of the prototype detector. The mechanical structure holding the PMTs can be seen as well as the light guides and the plastic strips. In the sides of the chamber, the PCB used as voltage dividers is also visible, as well as the LEMO and SHV feed-through. The PMTs can be separated from the frame containing the strips and the light guides using the black knobs in the upper and lower sides of the detector. A couple of handles attached to the frame can be used to easily remove and replace the set of strips and light guides. This is to note that the frame exchange is a fast process, which would require at most one hour. The FINGER detector will be placed inside a pocket. For this, an extra drive will be needed.

### 6.1.2 Electronics and data acquisition

The signals from each PMT will be transported to the processing electronics using high quality flexible coaxial flat cable. This type of cable was chosen to reduce the weight and the volume of the cables needed and to maintain best possible timing resolution from the detector. Due to the versatile design of the FINGER detector, the output of the PMTs can be directly soldered to the a Printed Circuit Board (PCB), which in turn can be plugged to the feed-through. The signals can be directed to the space allocated for the electronics using a flat cable. In Figure (22/a) and (22/b) an example of a connector to use and a sample of a flat cable have been shown respectively. It is possible to transport up to 30 signals in each cable, thus three flat cables are needed.

![Connector and Flexible flat cable](image)

**Figure 22.** Electronics components to be used in the new detector

For the power supply of the PMTs, it is foreseen to use the same strategy as in the previous FINGER detector and use voltage splitters to power up to four PMTs with a single channel of power supply. The voltage dividers will be built in a PCB, placed inside the detector chamber. With this setup a total of 25 HV power supplies is needed. The solution for the HV cables will be LEMO 5G series HV connectors, which allows to carry up to 50 HV lines. Standard power
supplies can be used. Power supplies with up to 32 channels providing 0-3 kV using standard SHV or radial multi-pin connector are commercially available. The signals from each PMT will be processed to obtain the timing and the energy of each one. LANDFEE, is providing the output signals whose length is proportional to the amplitude (and charge) of the input signals which can be used for energy measurement using the Time-over-Threshold (ToT) technique. This board also produces a trigger signal which might be used for external trigger logic and splits the input signal which can be optionally measured using a QDC. The LANDFEE discriminator has been successfully used in the prototype FINGER detector and continuation with the electronic developments produced in-house is recommended. The first option to consider for the readout of the new FINGER detector is the PADI discriminator board [36] which, as the LANDFEE, is capable of measuring both the leading ad the trailing edges of each signal. This board also has the possibility to split the signal in case an external VME QDC is preferred over the ToT. The timing signals produced by the PADI will be recorded using either a standard Multi-hit TDC from CAEN, or an in-house produced TAMEX or TAMEX2 TDC, having also multi-hit capabilities. It is of note that the FINGER detector will benefit from the continuing development in electronics by the R3B group and the Neu-LAND collaboration. In this sense, a second option which can be considered for the read-out electronics is the newly developed NeuLANDFTQ board, in which the LANDFEE, the QTC and the TRIPLEX board have been merged and optimized [37].

The Data Acquisition (DAQ) used will be based on the standard NUSTAR MBS DAQ system available. An option for the DAQ can be based on VME electronics read-out by the MBS system. A RIO6 controller or other type of available CPU can be used to interface the VME crate with the PC. For the trigger generation and synchronization, a TRIVA7 module can be used in combination with a VULOM5 trigger logic unit. Synchronization with the Super-FRS and with other detectors along the beam line will be based on the common White-Rabbit system, given that it is provided by the facility. As the detector serves for identification purposes, its trigger should be constrained to the experimental conditions. For this reason, no self-trigger will be produced and the detector will be read out using an external trigger. The electronics system has to be able to process a particle rate of about 10^7 pps.

### 6.1.3 Infrastructure and mechanics

The assembly of the new FINGER detector will be an improved version of the existing detector. Apart from the necessary increment in the dimensions of the detector, no major changes will be performed. Figure 23, shows the technical drawing of the FINGER detector prototype. The handles designed to manipulate the removable frame can be clearly seen. It can also be seen that these handles as well as the bending angle of the mechanical holder of the PMTs are the factor determining the width of the detector. Although the total width of the mechanical structure of the FINGER detector prototype is below 200 mm, it is planned to reduce this bending angle in order to make the full structure thinner and to facilitate its placement in the vacuum chamber. The upper plate of the mechanical structure holding the detector will host the flange and the drive to move the detector in and out of the beam line. Enough space is
provided to mount the drive. The flange will also contain the corresponding feed-through panels to connect the signals and the HV. The design of the flange depends on the drive used to move the detector. For the drive, it is intended to use a common design together with other Super-FRS detectors.

Figure 23. Technical Drawing of the FINGER detector prototype.

6.2 FLF3 and FLF4 beam tubes and pumps

There are three operation modes planned for the Super-FRS at the LEB: H/D, energy buncher, and high-resolution spectrometer. All of them (e.g., the HISPEC 200 mode in Fig. 7) require an XY-position detection in front of the multipole magnet on the beam exit of FLF3, and two of them require a vacuum beam pipe at FLF3 and FLF4 in addition to the diagnostics chamber. For H/D the diagnostic chambers will have to be mostly removed and therefore, the mounting procedure for the setup change will have to be established.
6.3 Enlargement of the AGATA frame

The existing AGATA frame will be enlarged from the present 10 triple detector support cones to $2\pi$ geometry. Similarly, the exit vacuum tube and cable guidance will have to be adopted to the new geometry. The existing AGATA support structure at GSI was designed structurally to support 30 triples (90 detectors) making it a $2\pi$ geometry. There will be further design required for a mounting arrangement in the LEB cave and for the exit vacuum tube and cable guidance system. The current system is mounted on rails that split the array perpendicular to the beam axes to allow access to the target. Rails mounted on the floor in the cave may not be allowed so this will also be investigated.

![Figure 24. (a) Technical Drawing of the existing AGATA structure. (b) The initial design scheme for the AGATA $2\pi$ geometry support structure.](image)

The AGATA collaboration is requesting that future designs can easily be expanded to a $4\pi$ geometry and that as much as possible of the support structure and associated mechanics can be reused at different laboratories. In Figure 24/a, technical drawing of the existing AGATA support structure is shown. The initial design scheme for a $2\pi$ geometry that can be duplicated to make $4\pi$ can be seen in the Figure 24/b. To use this arrangement at FAIR the current support structure and holding ring needs to be located behind the honeycomb.
6.4 Platforms and rail system for HISPEC and DESPEC experimental setups

The experimental setups for HISPEC and DESPEC will be installed on a common platform on rails. The overall size of the platform is approximately 2.5 x 4 m² allowing for mounting and transporting the maximal load of 5 tones (equivalent to the heaviest detector system: DEGAS-AIDA and the electronics racks) between the in-beam and off-beam positions. A desirable shift of the setups in the range of 2 to 3 m perpendicular to the beamline is considered in order to facilitate installation and to comply with the safety requirements – escape paths etc. (Fig. 25). The rails may be embedded in the concrete floor and the channels are covered when not in motion. The setups are installed on the platform on a second transversal set of rails, thus ensuring the positioning on the XY plane with a desired accuracy better than 1 mm. The platform is moved by electric motors with low speed and a certain number of sensors provide a good accuracy and reproducibility of the setup positioning. In order to ensure the mechanical stability of the structure in different configurations all the platform components are simulated using the FEM (Finite Element Method) calculations.

![Figure 25. Left- Design of the H/D platform with the motion system (electric engine and rails). Right- visualization of the DESPEC setup including AIDA and DEGAS detectors and related electronics racks placed on the platform in work position.](image-url)
6.5 Specification for implementing slowed down beam experiment

6.5.1 Beam line and Vacuum chamber

All the detectors must be placed in high vacuum (<10^{-6} mbar) because of the relatively low energy of the slowed down ions which would lose a significant amount of energy at air over a short distance. For efficient beam time usage the vacuum should be reachable in a day. It is desirable to have an oil-free vacuum to prevent contamination of chamber and detectors. A valve between beam line and scattering chamber would be beneficial to facilitate change of target and detectors. Both compartments need independent vacuum systems. Simulations with MOCADI show that the beam will be as wide as 20 cm in the dispersive plane after the slow down at FLF3. Hence, a special target chamber is required for this experiment with a broader entrance than the actual AGATA scattering chamber. In the AGATA detector array fits a sphere with a diameter of 35.4 cm. The side of the vacuum chamber pointing to the AGATA Array should be spherical. The beam line between the degrader and the target chamber should have at least the same size as the maximal scattering target size which is foreseen for the experiment. Standardized CF 200 parts fulfill this. They have a diameter about 20 cm so that almost all of the slowed down beam can be transported to the target. A thin uniform vacuum window will be needed in front of the beam line, e.g. 100-50 μm stainless steel. The beam line must contain the start unit of the beam tracking detector and must be as long as possible for the ToF measurement. Therefore, a beam line of 1.8 m, which fits in FLF3, is desired. Inside the beam line and the chamber the target and all the slow down beam detectors have to be mounted. The start detector of the ToF detector system will need a special separate vacuum chamber. The stop detector might need a special vacuum chamber too or is integrated in the scattering chamber.

If DemiSED detectors are used for tracking then a large vacuum chamber, of dimension 1.5 x 1 x 1 m^3 will be necessary to accommodate the magnet (copper coils) required to focus the electrons (Figure 26.). This chamber should be big enough to additionally accommodate the two DemiSEDs inside with a distance of 1 m between them. Four KF40 flanges with feedthrough to supply cooling water for the coils are needed. Also a CF200 flange mechanized with three KF16 tubes is necessary for inserting isobutene in the detector.
6.5.2 Detector sizes

There are different solutions for the experimental setup in discussion. One option is to mount the detector in a separate chamber upstream from the target chamber. The other option is to mount it inside the target chamber. The scattering chamber diameter is 35.4 cm, of which a shell of approx. 7 cm width will be expected to be occupied by the ΔE-E telescope, preamplifiers, cables etc. This limits the space available for target and the stop unit to a sphere of radius ~10.5 cm. How much of the solid angle of the sphere is used as scattering chamber, e.g. only one hemisphere (2π), is different for different solutions.

One can group the different solutions into two categories. The first category covers all the solutions with a target perpendicular to the beam. With this a maximal rectangular target size of ~15x15cm² or 21 cm diameter for a round target can be reached. In the simulation 80% respective 90% of the slowed down ions would hit the target. The ΔE –E telescope could cover the sphere up to the entrance and therefore also detect backward scattered ions. There will be 15 cm or 21 cm between the stop unit of the beam tracking detector and the target (Figure 27 (c)), so that the interaction point has to be extrapolated. In addition, a secondary electron emitting foil will be needed in which the beam will gain additional, but small energy and angular straggling. For these target sizes an MCP-based solution for the beam-tracking detector is not feasible. The second category uses a target which is tilted by 45° against the beam. The target is used as secondary electron emitter for the stop unit. Therefore, the interaction position is measured directly. Hence, the stop unit has to be in the scattering chamber together with the ΔE-E-telescope. The restriction results from the size of the target. An optimal stop unit with
the shortest drift length is a square box tilted 45° against the beam. One face of the box is the

**target. The maximal square box which can be inserted in a sphere is a cube with edge length**

\[ a = \frac{2R}{\sqrt{3}} \] 

(cf. Fig. 27 (a)). Due to the tilting the beam sees only a factor of \(1/\sqrt{2}\) less active

area. In our case this would mean 12.1 x 8.6 cm² effective target size. In addition, the target

size would have to sit above the beam axis. Therefore, only around 35% of the beam can be

used. If one changes the size of the detector so that the middle of the detection area/ target is at

the middle of the beam (cf. Fig. 27 (b)), the detector size shrinks to 9 x 9 cm², i.e effectively 9

x 6.4 cm² and 42% of the beam could be used.

The size of DemiSED detector is 300x260 mm². The detector is coupled to an emissive foil

of the same size and separated by 20 cm from the detector. The entire system is placed in the

middle of two coils as it was mentioned previously. If we consider the complete system

(detector + emissive foil + magnet) its dimension is around 400 x 420 x 560 mm³.

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**Figure 27 (a): Maximal Detector size and (b) Centered Detector configurations mounted inside the**

**AGATA scattering chamber. (c) Pictorial description of the extrapolation length for TOF**

**measurement (for MCP- based TOF stop detector).**

---

### 6.5.3 Secondary target

As discussed above the target size corresponds to the chosen detector configuration. One may

consider using the target as secondary electron emitter in combination with an MCP detector

for ToF and position measurement instead of a separated foil to reduce the additional angular

and energy straggling.
6.5.4 Cabling and vacuum feedthroughs

Vacuum feedthroughs for HV power supply of the detectors and for fast signals must be present. The maximal required HV will be below 3 kV. Therefore, SHV power connections are recommended. For the signals Lemo/BNC type feedthroughs or SMA feedthroughs for the fastest signals will be sufficient.

6.5.5 Electronics

The front-end electronics for the ToF measurement within 1 m are considered to be sufficient to reach 150 ps overall resolution.

6.6 DEGAS infrastructure

The DEGAS [9] mechanics consists of several main components:
- Main Frame
- Front Scintillator shield mechanics
- Side scintillator shield mechanics
- Front lead wall
- DEGAS Triples mechanics

The Setup is shown in Fig. 28.1. The shields mechanics and the triple mechanics are installed on a common table-like structure Fig.28.2. This allows removing and installing the detector components independently. The DEGAS triples are moved before to reach the operational position in a sort of barrel (fig.28.3) with a specific shape. At the operational position the triple is fixed by M8 screws. Additionally steel bars (or other suitable structure) utilizing the M10 threaded holes on the cryostat, may help by the installation.

The front shield and the side shields are fixed in advance and removing of any element of them is not foreseen, unless any repair is needed (Fig.28.4). The lead wall is fixed permanently as well.

The holding Main Frame structure is made by aluminum modular components (“ITEM-bars”) and has the possibility for adjusting the height of the detector assembly in order to fit properly to the beam
The Setup itself is mobile on the main platform, thus enabling manipulating of the DEGAS triples at the most appropriate position.

The grounding of the DEGAS detectors is through the Setup, thus it is grounded on the main grounding network.

The cooling system of DEGAS triples consist of heat exchangers with controlled output temperature, a pipes network with distributors and a support structure. The heat exchanger is a closed loop water heat exchanger type with a cooling power of 5 kW. The pipes network is with Ø8x1 pipes size (polypropylene) with blocking fast connectors. The supporting structure is integrated with the Setup.

The power supply of the DEGAS electronics uses 48 V DC, the coolers use 24 V DC and the Shield’s electronics is powered also by 24 V DC. The Power supply modules are mounted in a rack which is installed at the Main Platform. The cables are with average length of 12 m and are held by a supporting structure, possibly by the same supporting structure used for the water cooling system.

**Figure 28:** (1) The DEGAS array with its support structure, (2) Table-like structure for shields and triple mechanics, (3) Barrel for triples, (4) Side shield mounting.
6.7 Cabling

The cabling for the H/D experiments concern two cases:

1. Super-FRS tunnel at FMF2 and FLF2 where dedicated equipment for H/D is located
2. All focal planes in the LEB have dedicated cables for H/D experiments

For the two cases the cables go first to a patch panel close to the focal plane, which is connected to another patch panel where the racks are located. In the first case the racks are located in radiation protected niches alongside the separator. For the second case the racks are a few meters away from the main focal planes in the Low Energy Building. Those patch panels assure the presence at the focal plane of network ports, drive channels, interlock, White Rabbit timestamping signals and messages and of the BuTiS clocks. For each case the cables for the detector planes are included together with “user” cables for testing or debugging, part of them being high quality cables with low loss at high frequency. We opted for telecommunication standard for the panel to panel connection (LMR family) which assures some cost savings for the same or improved quality of the standard, nuclear physics specific albeit older specifications RG family.

Together with those point-to-point cables, some high quality cables are planned between the racks and places accessible during beam time to permit monitoring. In a similar fashion, some cables are reserved for sending signals along the focal planes, in case hardware triggers/validation would be needed.

6.8 HISPEC/DESPEC DAQ infrastructure and specific equipment

The NUSTAR DAQ TDR [38] defines the data acquisition basic infrastructure needed for the integration of the different elements in a common DAQ to be able to easily correlate and merge information from the Super-FRS identification detectors and the experiment setups of the other NUSTAR sub-collaborations. H/D will follow those guidelines and contribute in building this general infrastructure. Part of this infrastructure has already been bought for running HISPEC0/PreSPEC experiments.

Together with the components defined in the NUSTAR DAQ TDR, H/D will require specific equipment to be used exclusively by H/D. This will be some basic data acquisition system to be presented in the FLF3 and FLF4/6 focal planes for user detectors or configuration changes. It includes the specific monitoring for the H/D and the network and data acquisition infrastructure to receive specific H/D detectors (like AGATA or AIDA). Due to the AGATA campaign having run
in 2012/2014 part of this H/D specific DAQ equipment has been procured during this period, as the optical fibers for AGATA or part of electronic racks, which will be reused in FAIR. For the future implementation of AGATA DAQ a new electronic hut will be required which will contain all the racks needed and a high-quality, and low vibration level air conditioning system required by the intended neighborhood of the laser hut of the LASPEC collaboration.

7. Radiation Environment and Safety Issues

H/D is going to be operated in the NUSTAR Low-Energy-Cave, where low intensity primary and secondary radioactive ion beams will arrive. Hence, both short-lived and accumulated radioactivity is at a comparatively low level as, for example, at 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.

H/D uses HPGe detectors which are LN2 cooled (in case of HISPEC AGATA detectors, for DESPEC a target HPGe detector) and electrically cooled DEGAS. The HV supplies are mainly to operate AGATA, Ge-Target detector and tracking detectors. The DEGAS HV-supply is embedded in the preamplifier compartment of the cryostat. The HV-supplies are low and middle current supplies and the voltage does not exceed 6 kV. The crates are in special racks, properly grounded (also for EMC reason) and do need special protection by operation.

Strong magnetic fields must be avoided in areas where the personnel operate and it must be assured that no ferromagnetic objects can be deployed in the magnetic fields at any time. It is suggested to mark areas where magnetic fields could occur and to take care that nobody with heart pacemakers enters there when magnets are powered and any ferromagnetic objects are not placed in that area any time. As a principle, the magnets will not be powered when the cave is accessible.

The cryogenic systems utilizing liquid nitrogen (LN2), liquid hydrogen (LH2) which are serious safety concerns and liquid helium (LHe). Along the Super-FRS superconducting utilities, which are to be monitored in order to detect in time massive LN2 leakage, an oxygen monitoring circuitry, which warns when the oxygen concentration in the air is too low. The Autofill system of the AGATA detectors or other HPGe detectors utilizes buffer tanks for LN2 which are automatically refilled from the outside LN2 tanks. The Autofill controls not only the filling of the detectors and the tanks, but takes care of detecting of massive LN2 leaks and terminating any filling (detector or buffer tank) in an accidental massive leakage case. The safety of the LN2 delivery system is provided by the use of a vacuum insulated LN2 filling line and an integrated terminal.

The LH2 system poses especial danger and despite the care to avoid any release of H2 (or LH2) an aspiration system, installed above the LH2 target is to remove any residual hydrogen. Similar system is to be installed for removing of the gaseous N2 released during the operation and the filling of the LN2 cooled detectors.

The AGATA digitizers and DEGAS cooling engines utilize water heat exchangers in order to remove the heat. Nevertheless, that the water cooling operates in closed loop, the outer water supply
is connected by flexible pipes to the main heat exchanger. Each cooling line is connected by own pipes. Any water leak is not tolerable, because it may cause short cut and possible fire. A pipelines integrity monitoring system is to be deployed in order to cut off the water supply and switching the appliances off in case of water release.

The infrastructure systems are to be operated by well-trained personnel and any action in this field taken by the visiting scientist is not desirable. Therefore, the control systems GUI’s are to be designed on the principle of two layers – outer, which essentially allows only monitoring of the status and inner which is protected (passwords, codes, hardware protection etc.) and can be operated only by local personnel.

Special care will be devoted to liquid-scintillator detector arrays like MONSTER and NEDA, which is mostly described in those specific TDRs.

8. Production, Quality Assurance and Acceptance Tests

8.1 General

The production and quality assurance is guaranteed for almost all items as they are commercially available and/or included in another contract (Super-FRS). The acceptance test will be done at the FAIR site. The mechanical supports and large components before they will be installed at LEB will undergo detailed engineering tests.

8.2 FINGER Detector

Thanks to the fact that a great deal of experience has been gained by the design, mounting and use of the FINGER detector prototype, each one of the components will be tested by the FINGER detector collaboration. The assembly, quality assurance, and acceptance tests will also be performed by the collaboration, using the test benches at GSI. The laboratory testing will require a standard $^\beta$ radioactive source and a LED diode. Using the LED diode the proper optical mounting of the detector can be made and minimization of the cross-talk can be guaranteed. The proper operation of the PMTs can also be tested using the LED diode. The performance of the electronic modules will be performed using both the LED and the $^\beta$ source.
9. Calibration with test beams

Standard calibration test with beam as for all Super-FRS detectors will be needed. The commissioning test beam time of at least one week will be needed before each campaign to combine all the subsystems.

9.1 Calibration of TA-DSSSD

Standard Super-FRS beam calibration in the LEB will also be sufficient for TA-DSSSD detector position/energy calibration. It is assumed that it can be done in parallel to this procedure. All other preparatory work can be done in the lab.

9.2 FINGER detector calibration and commissioning

The set of strips and PMTs which form the FINGER detector have to be calibrated both in the laboratory and in-beam. The laboratory calibration aims at preliminary gain matching of each PMT in order to guarantee a first degree of homogeneity in the signals. This calibration can be performed using a LED diode and has been already tested in the prototype detector. The remaining spread in the PMTs gains can be corrected using an in-beam measurement of primary beam, for example. As it was pointed out, this detector is not intended to perform energy measurements and thus a more precise calibration is not critical. The calibration of the timing signals of each PMT has to be performed in-beam by comparing the signals to a single piece of plastic scintillator read out using as few PMTs as possible. Due to the fact that other detectors placed at FMF2 also need to be calibrated, a plastic scintillator is expected to be provided by the FRS collaboration or by their collaborators at the LYCCA collaboration. In case of need, the design of the FINGER detector can be modified to host an additional plastic scintillator. The effects of this additional piece of matter should be minimized, as the design of the FINGER detector would not allow this detector to be removed after calibration.
10. Civil engineering, cave, cooling, cranes etc.

10.1 General Requirement

The infrastructure described in this TDR and the needs of the whole H/D experiments were included in the construction planning of the LEB building and are specified in the following:

1. A staging area is required in the cave. It is suggested to use part of the open space left to the 2nd and 3rd dipole.
2. Tagging type experiments rely on low radiation background (from FLF3) at FLF6. It is suggested to keep the possibility to erect for the duration of such experiments a 1 m thick concrete block wall in the open space left to the 2nd and 3rd dipole.
3. The AGATA system requires an air-conditioned hut for data acquisition electronics which must be permanently accessible. A maximum of 420 fibers of < 100 m length are supposed to connect the AGATA set-up with this DAQ-hut. It is agreed to build and share this hut with the MATS/LASPEC hut in the MATS/LAPEC area, such that it does not interfere with the laser installation of LASPEC.
4. The main experimental areas of H/D require ultimate electrical grounding to avoid noise pickup. On other hand, it must not obstruct moving of heavy components by air cushions. Therefore, a specific grounding concept has been developed. The main grounding line is made out of copper strips with width 20-50 mm and thickness of 5 mm and is installed along the right and front walls (with respect to the beam direction). The experimental setup footprint is to be covered by removable galvanized iron plates, connected to the main grounding line. Since the DEGAS detector is with floating ground, no any specific grounding precautions are to be taken, simple connection to the most appropriate ground is sufficient. The AGATA Detector is not with floating ground and has to be grounded to the floor iron plates through the setup mechanics. Since the detector electronics (digitizers, power supplies etc.) is installed on the setup frame, the ground integrity is ensured naturally. The other detectors – AIDA (DESPEC relevant) or LYCCA (HISPEC relevant) are to be connected to the same ground plane.
5. Pressurized air, standard gases and standard cooling water are needed at the experimental areas at FLF3, 4 and 6.
6. LN2 pipe connections are required on both sides of FLF3 at the walls. The possibility to install an additional line from FLF3 to FLF6 along one wall needs to be kept.
10.2 Cabling and electrical power requirements

The H/D experiment will extend (depending on the experiment) over three focal planes FLF3, 4 and 6. Therefore cabling infrastructure is needed to combine them together as well as they will be combined with the rest of the Super-FRS for triggering reasons etc. This requirement is included in the following specification list:

1. Three sets of 5 water-cooled electronics racks are needed close to the three experimental areas at FLF3, 4 and 6, respectively. Each rack takes up to 5 kW power. A utilization factor of 2/3 should be assumed.
2. All racks should run on UPS. 3 sets of 4 racks should be on clean power. The electronics racks have to be connected to the floor iron plane by welding in order to deliver the best grounding. This requires a certain size of the iron plane to be considered.
3. Two water-cooled electronics racks are needed for permanent access electronics outside the cave. Each rack takes up to 5 kW clean UPS power. It is suggested to locate these racks in the AGATA DAQ hut.
4. Three sets of 30 high-quality signal cables are required to connect the three experimental areas at FLF3, 4 and 6 with the 2 outside racks. The length of these cables should be < 50 m.
5. Three sets of 20 standard network connections as well as BuTiS/White Rabbit infrastructure are required at the experimental areas at FLF3, 4 and 6.
6. Cable trays for up to 100 cables connecting the experimental areas at FLF3, 4 and 6 are needed.

10.3 FINGER Detector Requirement

It is planned to assembly the detector at the test benches available at GSI/FAIR. Due to the compact size of the detector, it can be easily transported to the experimental area where it should be attached to the corresponding flange and drive. This installation and alignment requires the use of a crane at the FMF2 area. The electronics racks can be placed in the designated areas out of the experimental hall where the cabling will be performed.
11. **Installation procedure, its time sequence, necessary logistics from A to Z including transportation**

It is assumed that the platforms for each experimental campaign of H/D can be installed and stored at its storage place inside the LEB cave. The infrastructure should be ready for the time of availability of the LEB cave in about 2022. All the infrastructure will be installed once all magnets and their infrastructure is in place. At the same time also the FINGER detector can be placed at FMF2. Installation of the various detector sub-systems is assumed to take place prior to dedicated campaign-like series of experiments. To maximize the physics exploitation of the detectors it is further assumed that they will be used at other facilities when not needed at FAIR. Thus no long-term storage space will be required.
References:

[6] RISING.
[14] MUSIC, "f-ds-bd-87e_sfrs_de_detector_v5.0, EDMS-ID: 1739046/5".
[22] M. W. Simon et al., "CHICO, a heavy ion detector for Gammasphere" Nucl. Instr. Meth. A,
**Common Abbreviations**

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>AGATA</td>
<td>Advanced GAmma Tracking Array</td>
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<tr>
<td>AIDA</td>
<td>Advanced Implantation Detector Array</td>
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<tr>
<td>BELEN</td>
<td>BEta deLayEd Neutron detector</td>
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<tr>
<td>DESPEC</td>
<td>Decay SPECtroscopy</td>
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<tr>
<td>DEGAS</td>
<td>DESPEC Germanium Array Spectrometer</td>
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<tr>
<td>DSSSD</td>
<td>Double Sided Silicon Strip Detector</td>
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<tr>
<td>DDL</td>
<td>Dual Delay Line</td>
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<tr>
<td>FATIMA</td>
<td>FAst TIMing array</td>
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<tr>
<td>FAIR</td>
<td>Facility for Antiproton and Ion Research</td>
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<tr>
<td>FRS</td>
<td>Fragment Separator</td>
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<tr>
<td>GEM</td>
<td>Gas Electron Multiplier</td>
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<tr>
<td>H/D</td>
<td>HISPEC/DESPEC</td>
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<tr>
<td>HISPEC</td>
<td>High Resolution Inflight SPECtroscopy</td>
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<tr>
<td>HYDE</td>
<td>HYbrid DEtector array</td>
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<tr>
<td>LEB</td>
<td>Low Energy Branch</td>
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<td>LYCCA</td>
<td>Lund-York-Cologne CAlorimeter</td>
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<tr>
<td>MWPC</td>
<td>Multi Wire Proportional Counters</td>
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<tr>
<td>MONSTER</td>
<td>MOdular Neutron time-of-flight SpectromeTER</td>
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<tr>
<td>MUSIC</td>
<td>MUlti Sampling Ionization Chamber</td>
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<tr>
<td>MCP</td>
<td>Micro -Channel plate</td>
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<tr>
<td>NEDA</td>
<td>NEutron Detector Array</td>
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<tr>
<td>NUSTAR</td>
<td>Nuclear Structure Astrophysics and Reaction</td>
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<tr>
<td>PGT</td>
<td>Particle Gamma Timing</td>
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<td>PID</td>
<td>Particle IDentity</td>
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<td>PMT</td>
<td>Photo Multiplier Tube</td>
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<tr>
<td>Super-FRS</td>
<td>Superconducting FRagment Separator</td>
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<tr>
<td>TDR</td>
<td>Technical Design Report</td>
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<tr>
<td>TOF</td>
<td>Time Of Flight</td>
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<tr>
<td>ToT</td>
<td>Time over Threshold</td>
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<tr>
<td>TPC</td>
<td>Time Projection Chamber</td>
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