1. Introduction

The realization of the new international project, Facility for Beams of Ions and Antiprotons (FAIR), has started at the GSI Laboratory in Darmstadt, Germany. The proposed schedule for building the facility extends over 8 years till 2015. The present estimate of the FAIR construction cost is more than 1 billion €.

The FAIR facility will provide an extensive range of particle beams from protons and antiprotons to ions of all chemical elements up to uranium with in many respects world record intensities. The new facility is built, and substantially expanded, on the present accelerator system at GSI, both in its research goals and its technical possibilities. It consists of a 100/300 T-m superconducting double-ring synchrotron SIS100/300 and a system of associated storage rings for beam collection, cooling, phase space optimization and experimentation (Fig. 1) and uses the present accelerators, a universal linear accelerator (UNILAC) and a synchrotron ring accelerator (SIS18) as injector.

A key feature of the new facility will be the generation of intense, high-quality secondary beams including beams of short-lived (radioactive) nuclei and beams of antiprotons. Compared to the present GSI facility, a factor of 100 in primary beam intensities and up to a factor of 10000 in secondary radioactive beam intensities are technical goals. The new facility will have possibility to provide beam energies much higher than presently available at GSI for all ions, from protons to uranium.

The beams which can be provided by the proposed synchrotrons and cooler/storage rings are:

**Primary Beams**
- $10^{12}$ s$^{-1}$, 1.5–2 GeV/u, ions up to $^{238}$U$^{28+}$
- $2 \times 10^{13}$ s$^{-1}$, 30 GeV, protons
- up to 90 GeV, protons
- $10^{10}$ s$^{-1}$, up to 35 GeV/u, $^{238}$U$^{73+}$

**Secondary Beams**
- broad range of radioactive beams, 1.5–2 GeV/u
- antiprotons, 3–30 GeV

**Storage and Cooler Rings**
- radioactive beams
- $\pi$–$\Lambda$ collider
- $10^{11}$ s$^{-1}$, stored and cooled antiprotons, 0.8–14.5 GeV

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**Fig. 1.** The existing GSI facility with the linear accelerator UNILAC, the heavy-ion synchrotron SIS18, the fragment separator FRS and the experiment storage ring ESR, and the new project with the double-ring synchrotron SIS100/300, the high-energy storage ring HESR, the collector ring CR, the new experiment storage ring NESR, the super-conducting fragment separator Super-FRS
FAIR will open up unique opportunities for a wide spectrum of research programs including QCD studies with cooled beams of antiprotons, nucleus-nucleus collisions at highest baryon density, nuclear structure and nuclear astrophysics investigations with nuclei far from stability, high density plasma physics, atomic and material science studies, radio-biological investigations and other interdisciplinary studies.

PNPI has a long term cooperation program with GSI. The nuclear spatial structure of the neutron-rich light nuclei by means of the proton elastic scattering in inverse kinematics using a proton recoil detector IKAR developed at PNPI has been investigated over last decade. Worldwide known are the experiments dedicated to mass measurements of exotic nuclides, which were performed with participation of the PNPI group at the ESR of GSI. It is quite natural for PNPI to continue and enforce its research activity at the new GSI facility.

Among the accepted FAIR projects there are NUSTAR, CBM and PANDA where PNPI is taking part. The experiments at FAIR, with PNPI participation, are shortly presented in this report.

2. Research with rare-isotope beams – nuclei far from stability

**Nuclear Structure and Astrophysics – NUSTAR project**

The main studies of nuclei far from stability will be performed in three research areas:

The structure of nuclei towards the limits of stability.

In the past, a major limitation in experiments studying nuclear reactions was that in any reaction both beam and target species needed to be stable. This imposed severe constraints on both the type of information that could be gained, and the region of nuclear chart that could be accessed. An availability of beams of unstable nuclei allows one to interchange the roles of beam and target particles to perform reaction studies in inverse kinematics. In this way many nuclides away from stability become accessible for detailed nuclear structure investigations of these weakly bound nuclei.

The structure and dynamics of such loosely bound nuclei is very different from that of stable nuclei. Rather diffuse surface zones, so-called halos and skins, were observed in neutron-rich unstable isotopes. Among other features unique to such exotic nuclei, one expects to encounter novel types of shell structures, new collective modes, new isospin pairing phases, possibly new decay modes (double proton emission) or regions of nuclei with specific deformations and symmetries. Effects of nucleonic clustering should become prominent, giving rise to unusual nuclear geometries.

Nuclear astrophysics.

The stable, heavy atomic nuclides found in our solar system have been produced in at least three processes, as it was concluded from their abundances. One of them, the slow neutron capture process ($s$-process) creating nuclides at the valley of beta-stability, is believed to be generally understood. Most of the heavy atomic nuclides, however, originate from an explosive process of nucleosynthesis, the so-called rapid neutron capture ($r$-process). A major goal of FAIR is to provide unstable nuclei near and beyond the $N = 126$ closed neutron shell, and to measure their masses, which govern the $r$-process, and their $\beta$-decay half-lives, which determine the accumulated abundance pattern along this path. Thereby a long-standing puzzle can be for the first time experimentally addressed, namely in what way the heaviest elements like thorium, uranium and their precursors have been created.

Neutron-deficient nuclides close to the proton drip-line are produced in other explosive scenarios. In these processes, hydrogen is explosively burnt via a sequence of rapid proton captures ($rp$-process) and $\beta^+\$-decays near the proton drip-line. Many of questions concerning the $rp$-process have not yet been answered. At the new GSI facility all relevant $rp$-nuclei will become accessible.

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1. See the report “Experimental study of nuclear spatial structure of neutron-rich He and Li isotopes”, this issue, p. 176.
2. The FAIR Conceptual Design Report, FAIR Technical Baseline Report and CBM, PANDA, R$^3$ ,MAIL1,EXL,B MATS experiments LOI were widely used in the preparation of this report.
Fundamental interactions and symmetries.

Many high-energy physics experiments are aimed to search for possible extensions of the Standard Model. Besides these investigations in particle physics, low-energy precise experiments in nuclear and atomic physics also show a unique discovery potential for this field. The nuclear physics studies will focus on the weak interaction, in particular on precise experiments of the β-decay of specific exotic nuclei. Such studies comprise accurate tests of parity and time-reversal symmetry, sensitive tests of the conserved vector current (CVC) hypothesis and sensitive searches for other than vector-axial vector (V−A) contributions to the weak interaction, such as scalar or tensor or (V+A) terms that would be a hint at the existence of additional exchange bosons of the weak interaction.

The studies with exotic beams are realized in frame of the NUSTAR project that includes seven independent subprojects. Among these there are R3B, EXL, ILIMA and MATS where PNPI is taking part.

2.1. R3B and EXL projects


The R3B (a universal setup for kinematical complete measurements of Reactions with Relativistic Radioactive Beams) will cover experimental reaction studies with exotic nuclei far from stability, with emphasis on nuclear structure and dynamics. Astrophysical aspects and technical applications are also considered. Reaction types and associated physics goals that can be achieved are given in Table. In case of light-ion scattering, the experiments at R3B are complementary to ones proposed for the internal target in the NESR (EXL project). The R3B program will focus on the most exotic short-lived nuclei which cannot be stored and cooled efficiently and on reactions with large-momentum transfer allowing the use of thick targets. The proposed experimental setup is adapted to the highest beam energies delivered by the Super-FRS, thus exploiting the highest possible transmission efficiency of secondary beams.

<table>
<thead>
<tr>
<th>Reaction type</th>
<th>Physics goals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Knockout</td>
<td>Shell structure, valence-nucleon wave function, many-particle decay channels, unbound states, nuclear resonances beyond the drip-lines</td>
</tr>
<tr>
<td>Quasi-free scattering</td>
<td>Single-particle spectral functions, shell-occupation probabilities, nucleon-nucleon correlations, cluster structures</td>
</tr>
<tr>
<td>Total absorption measurements</td>
<td>Nuclear matter radii, halo and skin structures</td>
</tr>
<tr>
<td>Elastic proton scattering</td>
<td>Nuclear matter densities, halo and skin structures</td>
</tr>
<tr>
<td>Heavy-ion induced electromagnetic excitation</td>
<td>Low-lying transition strength, single-particle structure, astrophysical s-factor, low-lying resonances in the continuum, giant dipole (quadrupole) strength</td>
</tr>
<tr>
<td>Charge exchange reactions</td>
<td>Gamow-Teller strength, soft excitation modes, spin-dipole resonance, neutron skin thickness</td>
</tr>
<tr>
<td>Projectile fragmentation and multifragmentation</td>
<td>Equation of state, thermal instabilities, structural phenomena in excited nuclei, γ-spectroscopy of exotic nuclei</td>
</tr>
<tr>
<td>Fission</td>
<td>Shell structure, dynamical properties</td>
</tr>
<tr>
<td>Spallation</td>
<td>Reaction mechanism, astrophysics, applications: nuclear-waste transmutation, neutron spallation sources</td>
</tr>
</tbody>
</table>

The proposed experimental scheme is based on that of the LAND apparatus which is used in experiments with secondary beams from the FRS facility at GSI. The most essential upgrades concern the target recoil detector and two magnetic spectrometers. A schematic view of the R3B experiment setup is shown in Fig. 2.
The incoming secondary beams are tracked and identified on an event-by-event basis. Measurements of the magnetic rigidity $B\rho$ (position measurement at the dispersive focus in the Super-FRS), time of flight TOF, and energy losses $\Delta E$ provide the isotope identification and momentum determination. Although the secondary beam has a momentum spread of $\pm 2.5\%$, the momentum will be determined to an accuracy of $10^{-4}$ (event-wise). After the target the forward focused projectile residues are again identified and the momentum is analyzed.

Two modes of operation are foreseen depending on the demands of the experiments:
1) A large-acceptance mode: heavy fragments and light charged particles (i.e. protons) are deflected by a large-acceptance dipole magnet and detected with a full solid-angle acceptance for the most reactions (left bend in Fig. 2). Resolutions for velocity and $B\rho$ measurements amount to about $10^{-3}$ allowing a unique identification in mass and nuclear charge of heavy fragments.
2) A high-resolution mode: here the dipole magnet is operated in reverse mode deflecting the fragments into magnetic spectrometer (right bend in Fig. 2). The envisaged resolution of $10^{-4}$ will allow a precise measurement of the fragment recoil momentum in single-nucleon knockout and quasi-free scattering experiments even for heavy nuclei.

The large gap of the dipole magnet provides a free cone of $\pm 80$ mrad for the neutrons which are detected in the forward direction by the large area neutron detector. At beam energies around 500 MeV/nucleon this corresponds to a 100% acceptance for neutrons with kinetic energies up to 5 MeV in the projectile rest frame. Depending on the requirements on resolution and acceptance, the detector with an active area of $2 \times 2$ m$^2$ is placed at a distance of 10 to 35 m from the target.

**Fig. 2.** Schematic drawing of the experimental setup comprising $\gamma$-rays and target recoil detection, a large-acceptance dipole magnet, a high-resolution magnetic spectrometer, neutron and light-charged particle detectors, and a variety of heavy-ion detectors

The target is surrounded by a $\gamma$-rays spectrometer. For most of the experiments a high efficiency total absorption spectrometer (cooled CsI) is the optimum solution which is also used to measure the energy of recoiling protons. For specific experiments requiring ultimate energy resolution for $\gamma$-detection, the germanium spectrometer will be used alternatively. For elastic, inelastic and quasi-free scattering experiments or charge exchange reactions, liquid or frozen hydrogen targets are considered. Recoiling protons and neutrons are detected by a Si-strip array and plastic scintillators, respectively. The Si-strip array is also used as a high-granularity multiplicity detector for measuring charged particles from the fireball created in semi-peripheral collisions. For measurements at low momentum transfer the use of an active target is foreseen. Fast neutrons stemming from $(p, pn)$-type knockout processes will be measured by placing part of the LAND detector at angles around 45°. Fast protons will be measured by two stations of large-area ($100 \times 80$ cm$^2$) drift chambers measuring X- and Y-coordinates, each with required spatial precision of $\sigma \leq 200$ $\mu$m. For each coordinate two drift cell layers, each cell has a hexagonal geometry, are used to resolve the left-right ambiguity. The drift chambers with readout electronics CROS3 have been designed and assembled at PNPI. In March 2007 the chambers were commissioned with the 500 MeV beam of $^{12}$C at GSI. Fig. 3 shows the detector setup in the test beam. First results of the test are presented in Figs. 4, 5.
The EXL project (EXotic nuclei studies in Light-ion induced reactions) aims at studying the structure of exotic nuclei in light-ion scattering experiments in the inverse kinematics at intermediate energies (100–700 MeV/nucleon) using an internal target placed in the NESR storage-cooler ring of FAIR (see Fig. 1).

The EXL physics program has some overlap with that proposed in the R3B project (see Table) as far as light-ion scattering is considered there. In the particular case of exploiting the active target concept within R3B, for measurements at low momentum transfer, the two projects are actually complementary. For nuclear lifetimes around or below one second, where there is no enough time for beam preparation in the CR/NESR rings and for continuous accumulation and stacking, measurements with the external target (R3B) are of preference. For longer lifetimes, cooling and beam accumulation in the storage ring should provide superior conditions. Keeping in mind that the rate capability of the active target technique will be limited, especially for very heavy projectiles, to about $10^5$ s$^{-1}$ or less, luminosities of the order 10$^{28}$ cm$^{-2}$s$^{-1}$, as expected for EXL, will not be reachable with the external active target.

The experimental setup shown in Fig. 6 (right side) comprises (1) a silicon target-recoil detector for charged particles, completed by $\gamma$-rays and slow-neutron detectors, located around the internal target, (2) forward detectors for fast ejectiles (both charged particles and neutrons) and (3) an in-ring heavy-ion spectrometer.

Secondary beams are transferred from the fragment separator (Super-FRS) to the collector ring (CR) at a fixed energy of 740 MeV/nucleon for collection and stochastic pre-cooling to a relative momentum spread around $10^{-4}$ and an emittance of 1 mm $\times$ mrad within a cooling time below one second. The beam quality will be further improved by electron cooling in the NESR. The NESR will be equipped with a supersonic jet target having densities of $10^{14}$–$10^{15}$ atoms/cm$^3$ for the hydrogen and helium targets.

The design and construction of the universal detector is one of the most challenging tasks of the EXL project. The charged recoil particles will be detected by array of silicon detectors in an energy interval from about 100 keV up to several hundred MeV and in an angular region of $30^\circ < \Theta_{lab} < 120^\circ$. An overview of the detector geometry (horizontal cross section through the mid plane) is displayed in Fig. 6 (left side). Different
regions A-E of the lab-angular range correspond to a color code as defined in the Fig. 6. Except for the regions C and D, where particle tracking is foreseen, the angular resolution will be determined by the dimension of the gas-jet target and the distance of the detectors from the interaction point. Therefore a distance of 50 cm of the detectors in regions where highest angular resolution is required was chosen to obtain an angular resolution of $\theta_{\text{lab}} \leq 2$ mrad for a target extension of 1 mm. For measurements at larger momentum transfer performed in regions C and D, a larger target extension in beam direction up to 5–10 mm may considerably increase the luminosity.

The detectors for region A, for example, are $\Delta E$-$E$ telescopes consisting of a double-sided silicon strip detector (DSSD), 300 $\mu$m thick, and a 9 mm thick lithium drifted silicon detector (Si(Li)) behind. Low-energy recoils from elastic scattering near 90°, as well as from charge exchange reactions with positive $Q$-values, will be stopped in the DSSD, whereas higher energy recoils (up to 45 MeV protons and 170 MeV $\alpha$-particles) will be stopped in the Si(Li). Therefore an energy threshold as low as 100 keV for the DSSD and a large dynamic range of 100 keV – 170 MeV for the combined telescope of DSSD and Si(Li) is required.

Total numbers of different types of DSSD and Si(Li) are: DSSD ~ 420, Si(Li) ~ 280.

At present, PNPI is carrying out the R&D on elaborating the $87 \times 87$ mm$^2$ and 9 mm thick Si(Li) detectors.

The scintillation hodoscope (see Fig. 6), behind the silicon array, is planned to detect $\gamma$-rays emitted from excited beam-like reaction products as well as the residual kinetic energy of fast target-like reaction products which punch through the silicon detectors. Almost $4\pi$ coverage, sufficient detector thickness for $\sim 80\%$ $\gamma$-detection efficiency at $E_\gamma = 2–4$ MeV and for stopping of up to 300 MeV protons, an energy resolution of $2–3\%$ for $\gamma$-rays and at least $1\%$ for fast protons are supposed.

For a kinematically complete measurement, the momenta of the light particles (protons and neutrons or light clusters) emitted from the excited projectile will be determined from high-resolution time-of-flight and position measurements. In a first phase of the EXL detector implementation, the existing LAND detector will be used, for the second phase a new neutron and charged particle detector based on a RPC structure is foreseen.

The heavy projectile fragments will be detected by in-ring spectrometer. Two layers of position-sensitive ion detectors will be placed in front and behind the third dipole magnet (see Fig. 6) allowing to track the ions and to determine their rigidity.
2.2. Mass measurements and decay spectroscopy – ILIMA and MATS projects


Nuclear masses and lifetimes of exotic nuclides in ground and isomeric states are the quantities essential for understanding the nuclear structure. The chart of nuclides with known and unknown masses is presented in Fig. 7, with the variation of neutron (proton) number along isotopic (isotonic) chains. From systematic precise mass measurements the important information such as location of drip-lines, the development of shell closures, the changes in shapes, pairing, and isospin symmetry can be derived. Beyond nuclear structure physics, precise mass values combined with decay spectroscopy are important for a variety of applications, ranging from nuclear-decay studies of the weak interaction and the Standard Model to astrophysical models for X-rays bursts and the creation of elements in stars.

Fig. 7. The chart of nuclides with known and unknown masses. The range of the mass measurements performed presently in the storage ring ESR at GSI and nuclides with still unknown masses, which will become accessible with the new facilities, the Super-FRS, the double storage ring system of CR and NESR, are indicated. Astrophysical r- and rp-processes are shown as well.

A real advantage is that at FAIR not only ground state properties can be studied, but also those of isomeric states which are populated in projectile fragmentation and fission reactions at relativistic energies. The experimental possibilities will expand the availability of pure isomeric beams that can be used for secondary nuclear reactions opening the novel way to explore the nuclear structure. The investigations at FAIR proposed by two complementary projects ILIMA and MATS will focus on:

1. mapping the large areas of unknown mass surface:
   • near and at the drip-lines, e.g. to investigate pairing among loosely bound nucleons,
   • N ≈ Z nuclei, e.g. to investigate the role of the neutron-proton pairing,
   • in the region of shell closures, e.g. around doubly magic nuclides $^{48}$Ni, $^{76}$Ni, $^{100}$Sn and $^{132}$Sn,
   • along specific chains of isotopes and isotones, e.g. to explore predicted shell quenching far from stability,
   • at the pathways of nucleosynthesis in stars (r- and rp-processes), in particular waiting points,
2. lifetimes of highly-charged ions, their decay modes and branching ratios,
3. mass-resolved isomeric states and related nuclear properties,
4. the production of pure isomeric beams and investigations with them.

2.2.1. Study of Isomeric Beams, Lifetimes and Masses – ILIMA project

Mass measurements of exotic nuclei are a challenge because of the low production cross sections and the inherent large emittance and longitudinal momentum spread of radioactive beams. A further difficulty arises from the fact that the nuclides close to the drip-line are short-lived and thus limit the time of preparation and observation. Two methods, both with sensitivity down to single ions, have been developed at GSI for
accurate mass measurements of stored exotic nuclei at relativistic energies: Schottky Mass Spectrometry (SMS) for cooled beams of long-lived isotopes and Isochronous Mass Spectrometry (IMS) for hot beams of short-lived (down to microsecond range) fragments. Both methods, providing the mass resolving power of about $10^6$ and accuracy of 30–50 microunits, are based on precise measurements of the revolution frequency which unambiguously characterizes the mass-to-charge ratio of the circulating in the ring ions. In SMS the velocity spread of the relativistic hot fragment beams is reduced by electron cooling. For IMS the ring optics is tuned to an isochronous mode such that the differences in velocities are compensated by different trajectories. These two methods are especially well-suited to measure effectively a large part of the mass surface in one run. In this way the systematic errors can be kept small if the reference masses for the calibration are reliable. The corresponding mass measurements in the Penning trap system (MATS project) of the Low-Energy Branch can provide very accurate reference masses.

The lifetimes of stored nuclei can be obtained with two independent methods. The first one is to measure non-destructively the intensity of both the mother and the daughter stored ion beams. These changes of the intensity are measured by applying Schottky spectrometry. The second one is based on the fact that the daughter and mother nuclides differ by their mass-to-charge ratio. Thus, the resulting daughter nuclei can be recorded with particle detectors placed near the orbit of the mother nuclides while the intensity of the mother nuclides is monitored by Schottky spectrometry. Both methods yield redundant information by a simultaneous measurement of the decay of the mother and the population of the daughter nuclides.

The experimental setup is schematically illustrated in Fig. 8. Experiments involving the nuclei with very short half-lives, down to $\mu$s range, will be performed in the CR operated in isochronous mode.

The experimental equipment in the CR will include time-of-flight detectors and sensitive Schottky probes, both enable precise revolution frequency measurements in very short time. Longer-lived nuclides (longer than 1 s) will be stochastically precooled in the CR and be transferred via RESR to the NESR for further electron cooling and measurements. An independent measurement of the lifetimes will be performed by measuring the daughter nucleus in particle-identification detectors placed near the closed orbit of the stored beam in both rings.

**Fig. 8.** The storage ring facilities for direct mass and half-life measurements and studies with isomeric beams

The combination of the Super-FRS with storage rings will provide access to pure isomeric beams. Already with the present FRS, the $Bp-\Delta E-Bp$ method provides monoisotopic beams in the storage ring ESR as illustrated in Fig. 9. In the left panel of this Figure a Schottky spectrum is shown for the case when the FRS is operated as a pure magnetic-rigidity analyzer. Applying the energy-loss separation with shaped degraders leads to a pure monoisotopic beam of $^{52}$Mn circulating in the ESR (right panel). Figure 9 demonstrates possibility to observe ground and isomeric states. In the $^{52}$Mn case the excitation energy of the isomeric state is merely 378 keV.
2.2.2. Precision Measurements of very short-lived nuclei using an Advanced Trapping System for highly-charged beams – MATS project

The MATS experiment will provide the mass measurements with relative uncertainty below $10^{-8}$, accuracy better than 1 microunit, for radionuclides which most often have half-lives well below 1 s. Substantial progress in Penning trap mass spectrometry has made this method a prime choice for high precision mass measurements of rare isotopes. The technique has the potential to maintain high accuracy and sensitivity even for very short-lived nuclides. Furthermore, ion traps can be used and offer advantages for precision decay studies due to the well-defined storage conditions that are free of impurities.

The MATS setup, as schematically shown in Fig. 10, is a unique combination of an electron beam ion trap for charge breeding, Paul and Penning traps for beam preparation and a high-precision Penning trap system for mass measurements and in-trap spectroscopy of conversion-electron and alpha decays. A relative mass uncertainty of $10^{-9}$ can be reached by employing highly-charged ions and non-destructive Fourier-Transform-Ion-Cyclotron-Resonance (FT-ICR) detection technique on a single stored ion. The high charge state of the ions can also be advantageously used to reduce the required storage time, hence making measurements on even shorter-lived isotopes possible.

Fig. 9. Schottky spectra of stored fragments in the ESR. Left panel: the FRS is used as a magnetic-rigidity analyzer resulting in an isotope-coctail beam in the storage ring where the $B_\rho$-$\Delta E$-$B_\rho$ separation method provides monoisotopic beams as demonstrated for $^{52}$Mn ions (right panel). The stored $^{52}$Mn ions consist of nuclei in the ground and isomeric states which are resolved by SMS, see zoomed part in the right panel.

Fig. 10. High-precision Penning trap mass spectrometer and in-trap conversion electron spectroscopy setup.
Decay studies in ion traps will become possible with MATS. Novel spectroscopic tools for in-trap high resolution conversion-electron and charged-particles spectroscopy from carrier-free sources will be developed aiming at the measurements of quadrupole moments and $E_0$ strengths. With the possibility both high precision mass measurements of shortest-lived isotopes and sensitive decay studies MATS is ideally suited to the investigation of very exotic nuclides that will only be produced at the FAIR facility.

PNPI contributes in the following activities:
- R&D and manufacturing the Si-detectors of different sizes (for particle detection in ILIMA and assisted spectroscopy at MATS).
- Simulation of the ion transport through the Penning trap system (for MATS and HITRAP/NESR – system).
- R&D of Penning trap with multi-segmented electrostatic field, partial manufacturing and assembling.

3. Compressed Baryonic Matter Experiment – CBM project


The scientific goal of the CBM research program is to explore the phase diagram of strongly interacting matter in the region of highest baryon densities. This approach is complementary to the activities at RHIC (Brookhaven) and ALICE (CERN-LHC) which concentrate on the region of high temperatures and very low net baryon densities. The territory of dense baryonic matter accessible in heavy-ion collisions is located between the line of chemical freeze-out and the hadronic/partonic phase boundary, as indicated by the hatched area in Fig. 11. New states of matter beyond the deconfinement and chiral transition at high baryon densities and moderate temperatures may be within the reach of the experiment. The proposed CBM experimental program includes topics which are of fundamental interest for both astrophysics and QCD:
- the study of in-medium properties of hadrons,
- the search for the chiral and deconfinement phase transition at high baryon densities,
- the search for the critical point of strongly interacting matter,
- the study of the nuclear equation-of-state of baryonic matter at high densities (as it exists in the interior of neutron stars),
- the search for new states of matter at high baryon densities.

Fig. 11. The phase diagram of strongly interacting matter. The red symbols represent freeze-out points obtained with a statistical model analysis from particle ratios measured in heavy collisions. The pink curve refers to a calculation of the chemical freeze-out which occurs at a constant density (baryons + antibaryons) of $\rho_B = 0.75 \rho_0$ (with $\rho_0 = 0.16 \text{ fm}^{-3}$). The blue curve represents the phase boundary as obtained with a QCD lattice calculation with a “critical point” (blue dot) at $T=160 \pm 3.5 \text{ MeV}$ and $\mu_B=725 \pm 35 \text{ MeV}$ ($\rho_B \approx 3 \rho_0$). In the region of the blue circle the baryon density is $\rho_B = 0.038 \text{ fm}^{-3} \approx 0.24 \rho_0$ (“dilute hadronic medium”). The corresponding value for the red circles is $\rho_B = 1.0 \text{ fm}^{-3} \approx 6.2 \rho_0$ (“dense baryonic medium”). The hatched area marks the region of equilibrated matter at high baryon densities.
The CBM experiment aims at comprehensive studying hadrons, muons, electrons and photons in heavy ion collisions. The key observables include:

- Low-mass vector mesons ($\rho$, $\omega$, $\phi$) decaying into $e^+e^-$ ($\mu^+\mu^-$) pairs. Via the measurement of penetrating probes one can extract the in-medium spectral function of mesons and, hence, obtain information on the possible restoration of chiral symmetry in dense baryonic matter.
- Hidden and open charm (charmonium, $D$ mesons). The measurement of charmed mesons at threshold beam energies will help in understanding the in-medium production processes and the properties of highly compressed strongly-interacting matter.
- (Multi-) Strange baryons ($\Lambda$, $\Xi$, $\Omega$). The yields and phase-space distributions of baryons containing (newly created) strange quarks are expected to be sensitive to the early and dense stage of collision.
- Global features like the collective flow and critical event by event fluctuations. These observables contain information on the nuclear equation-of-state at high densities and on the existence of a critical point, and, hence, on the location and the order of the deconfinement phase transition.
- Direct photons from first collisions and thermal photons from the dense and hot fireball.
- Exotica like pentaquarks, bound kaonic systems, strange clusters, precursor effects of a color superconducting phase, etc. The creation of compressed baryonic matter possibly will lead to unexpected phenomena.

The main experimental objective is the measurement of extremely rare signals in an environment typical for heavy-ion collisions. This requires the collection of a huge number of events which can only be obtained by very high reaction rates and long data taking periods. The CBM aims at reaction rates of up to 10 MHz (minimum bias) which corresponds to a beam intensity of $10^9$ particles per second on a 1% interaction target. The rear signals are embedded in a large background of charged particles. For example, a central Au+Au collision at 25 $A$-GeV produces about 1000 charged particles which in addition create a similar amount of secondaries via reactions in the target and detector materials. Hence, the experimental challenge is to measure about $10^{10}$ charged particles per second, which are focused into a small cone, and to identify rare particles.

The layout of the CBM experimental setup is optimized for heavy-ion collisions in the beam energy range from about 8 to 45 $A$-GeV. Experiments on dilepton production at beam energies from 2 to about 8 $A$-GeV could be carried out with the HADES spectrometer if installed in front of the CBM target (at present time the HADES is acting in GSI).

A schematic view of the proposed CBM detector concept is shown in Fig. 12.

Fig. 12. Schematic view of the CBM experiment. The setup consists of a high resolution Silicon Tracking System (STS), a Ring Imaging Cherenkov detector (RICH), three stations of Transition Radiation Detectors (TRD), a time-of-flight (TOF) system made of Resistive Plate Chambers (RPC) and an Electromagnetic Calorimeter (ECAL)
The core of the setup is a Silicon Tracking System (STS) located inside the large gap of the superconducting dipole magnet. The STS consists of several planar layers of silicon-pixel and silicon microstrip detectors which have to provide the capabilities for track reconstruction, determination of primary and secondary vertices with a resolution of better than 50 μm, and momentum determination with Δp/p < 1% in the range of 0.5 < p [GeV/c] < 4.0. Electrons from low-mass vector mesons decays will be identified with a Ring Imaging Cherenkov (RICH) detector. A Transition Radiation Detector (TRD) will provide charged particle tracking and the identification of high energy electrons and positrons. The hadron identification will be performed using a TOF wall of a Resistive Plate Chamber (RPC) array. The start signal for the TOF measurement will be taken from a diamond pixel (or micro-strip) detector. An Electromagnetic Calorimeter (ECAL) will be used for the identification of electrons and photons.

One of the major tasks of the CBM experiment is the measurement of open charm. D mesons will be detected via their weak decay into charged pions and kaons. This measurement poses a major challenge to the STS: the decay vertex of the D meson, which is displaced from the main vertex of the collision by several 10 μm, has to be determined with an accuracy of about 50 μm in order to suppress the combinatorial background caused by pions and kaons directly emitted from the fireball. The simulations show that an event suppression factor of about 1000 can be achieved when using a thin and highly granulated vertex pixel detector.

Another key observables are low-mass vector mesons which decay into lepton pairs with a branching ratio of 10^{-4}–10^{-5}. The major challenge, both for the measurement and for the data analysis, is to reject the physical background of electron-positron pairs from Dalitz decays and gamma conversion. As an alternative (or complementary) approach to the dielectron measurement is to study the possibility of detecting vector mesons ($\rho$, $\omega$, $\phi$, $J/\psi$) via their decay into $\mu^+\mu^-$ pairs. The idea is to replace the RICH detector by a “compact” muon absorber-detector system (Fig. 13) and to identify the muons just behind the STS. This configuration could work at the first stage of experiment as independent part of the CBM experiment. The simulations are based on track reconstruction algorithms taking into account a realistic response of the STS and of the muon chambers. Reconstructed charged particle tracks with hits in the muon chambers located behind the last absorber layer are associated with muons. The results of preliminary studies demonstrate the feasibility of dimuon measurements with the CBM detector setup using an active absorber, 5 Fe absorbers and 15 tracking detector layers, for Au+Au collisions at 25 A-GeV. This is particularly true for $J/\psi$ mesons which can be identified within the full phase-space acceptance of the CBM setup with a signal-to-background ratio of 10–100.

![Fig. 13. Location of the “compact” muon detector](image)

Preliminarily, PNPI contributes in the CBM project in several directions:

- Simulations to optimize the absorber and detector layout of the muon system aiming at receiving an acceptable signal-to-background ratio, especially in case of light vector mesons.
- Elaborating the muon tracking system, with special care for the central part where the highest rate and occupancy present. For today the muon tracking system might be a combination of micro-pattern gas detectors (such as GEM, Micromegas) for the central part and multiwire proportional chambers with cathode
readout to cover rest peripheral part of the aperture. R&D on the choice of the appropriate detectors is on the way.

• R&D of the tracking system for the TRT stations. At the present time, two variants are considered, one is based on the micro-drift chambers and the straw tubes are used in an alternative version. PNPI works on the straw tube approach.

• Mechanical design of the RICH detector.

4. Strong interaction studies with antiprotons – PANDA project (AntiProton Annihilations at Darmstadt)

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The PANDA project aims at studying the structure of hadrons and their interaction with medium using cooled antiproton beams of unprecedented quality and intensity in the momentum range of 1.5–15 GeV/c stored in the High Energy Storage Ring (HESR, see Fig. 1).

The physics program formulated for PANDA experiment will cover the following research directions:

• Charmonium (c\(\bar{c}\)) spectroscopy: precision measurements of mass, width, decay branches of all charmonium states, especially for extracting information on the quark confinement.

• Firm establishment of the QCD-predicted gluonic excitations (charmed hybrids, glueballs) in the charmonium mass range (3–5 GeV/c\(^2\)).

• Search for modifications of meson properties in the nuclear medium, and their possible relationship to the partial restoration of chiral symmetry for light quarks. Particular emphasis is placed on mesons with open and hidden charm in order to learn more about the origin of hadron masses.

• Precision \(\gamma\)-rays spectroscopy of single and double hypernuclei for extracting information on their structure and on the hyperon-nucleon and hyperon-hyperon interaction.

With increasing luminosity of the HESR facility further possibilities will emerge:

• \(D\)-meson decay spectroscopy (rare leptonic and hadronic decays).

• Search for \(CP\)-violation in the charm and strangeness sector (\(D\)-meson decays, \(\Lambda\bar{\Lambda}\) system).

• Extraction of generalized parton distributions from \(pp\) annihilation.

• Fundamental physics with stopped antiprotons.

The experiments will be performed at an internal target station of the HESR (see Fig. 14).
Antiprotons traversing the target material without interaction are recirculated in the ring passing through the electron cooler which compensates the energy loss and straggling and thus maintains the high beam quality. The minimum momentum of the antiprotons is 1.5 GeV/c and the maximum is 15 GeV/c. The maximum energy in the center-of-mass system for antiproton-proton collisions is 5.5 GeV, sufficient for associated production of singly charmed baryons (up to $\Omega_c$) and corresponding to the upper mass range predicted for charmonium hybrid states. Figure 15 shows the mass range of hadrons reachable at the HESP antiproton beam. Stochastic cooling of the beam over the whole energy range provides a momentum spread of $\Delta p/p \approx 10^{-4}$. In order to perform high precision charmonium spectroscopy, beam properties (at momentum below 8 GeV/c) will be improved by high energy electron cooling providing the momentum spread of $10^{-5}$ for the $\vec{p}$ beam.

The physics program puts stringent requirements on the detector. It has to accept the high rate of $2 \times 10^7$ annihilations per second at full luminosity originating from the total cross section of about 100 mb and simultaneously to allow for triggering events with nb cross section, involving $(e^+e^-)$, $(\mu^+\mu^-)$, $(\gamma\gamma)$, $(\phi\phi)$ pairs.

For the major part of the experimental program (charmonium spectroscopy, the search for hybrids and glueballs, and the interaction of hidden and open charm particles with nucleons and nuclei) a general purpose detector will be used (see Fig. 16). The inner part of the detector can be modified for the experiments with strange hypernuclei or for the special needs of CP-violation studies. In order to retain the full information in particular for spectroscopy experiments, a nearly full coverage of the solid angle together with a good particle identification and high energy and angular resolutions for charged particles ($\pi^\pm$, $K^\pm$) and photons is necessary.

The PANDA detector is subdivided into the target spectrometer (TS) consisting of a solenoid around the interaction region and the forward spectrometer (FS) based on a dipole magnet for momentum analysis of the forward going particles.

It is planning the use of a pellet target for most experiments at the HESR facility. However, depending upon the amount of beam heating from the internal target, it may be necessary to use also a gas jet target. The remaining experiments that require a very precise primary vertex determination will use a thin fiber or wire target.

Particles emitted with laboratory polar angles larger than 5° are measured in the TS. Surrounding the interaction volume there will be 4 diamond or Si start detectors (each of 20×30 mm$^2$) followed by 5 layers of a silicon Micro-Vertex Detector (MVD). Starting from a radial distance of 12 cm from the beam-line up to 42 cm, there will be 15 double-layers of crossed straw tubes or a Time Projection Chamber (TPC), which extend from 40 cm upstream to 110 cm downstream of the target. At a radial distance of 45 cm there will be a layer of DIRC Cherenkov detectors. Surrounding the target region there is an electromagnetic calorimeter. This calorimeter consists of PbWO$_4$ crystals that are readout with avalanche photodiodes (APD). The use of PbWO$_4$ is required for higher granularity and shorter dead-time. The smaller Molière radius of PbWO$_4$ furthermore reduces the dead space at the edge of the spectrometer. In the region between the calorimeter
and the endcap there will be 2 sets of mini-drift chambers (MDC) with 6 active planes each. In the forward direction there is an aerogel Cherenkov detector using proximity focusing onto gas based photon detectors. The TS is contained in a 2.5 m long and 80 cm radius solenoid. Behind the return yoke there will be scintillating strips for muon identification.

![Diagram](image.png)

**Fig. 16.** Top view of the general purpose PANDA spectrometer for antiproton annihilation physics

Particles emitted with polar angles below 10° and 5° in the horizontal and vertical direction, respectively, are detected with the forward spectrometer (FS). The current design includes a 1 m gap dipole magnet (total bending strength of 2 Tm) and tracking detectors for a momentum analysis of charged particles, i.e. mini-drift chambers (MDC) and straw-tube trackers (STT). Photons will be detected by a shashlyk-type calorimeter consisting of lead-scintillator sandwiches (EMC). Other neutral and charged particles with momenta close to the beam momentum will be detected in the hadron calorimeter and muon counters. Additional RICH detector, like at the HERMES experiment, and time-of-flight measurements are required for particle identification. Particle identification for hadrons and leptons over a large range of solid angles and momenta is an essential requirement for the PANDA experiment. Several dedicated systems, complementary to the other detectors, will provide means to identify particles. A time-of-flight (TOF) system will include TOF start detectors in the MVD, a TOF barrel between STT/TPC and DIRC, a flat layer of TOF detectors in the endcap, TOF stop counters inserted into the dipole magnet of the FS, and a large TOF stop wall in the FS. Cherenkov detectors will enlarge the capabilities of this system to the high momenta where times of flight are too short for TOF measurements. In certain momentum ranges the particle identification will be done by using energy losses in the detectors (MVD for slow charged particles, EMC for γ-rays and leptons).

PNPI is responsible, and at the present time is conducting an intensive R&D, for elaborating the TOF stop detectors in the forward spectrometer. These detectors will consist of tiles made of plastic scintillator and read out on both ends by fast phototubes. Such counters will be placed as a wall about 7 m from the target and inside the dipole magnet opening. With the expected time resolution of $\sigma = 50$ ps, $\pi$-$K$ and $K$-$p$ separation on a $3\sigma$ level will be possible up to momenta 2.8 GeV/c and 4.7 GeV/c, respectively.