PROCEEDINGS OF SCIENCE

Development of silicon tracking detectors for FAIR

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The international research facility FAIR is under realization next to the GSI Laboratory in Darmstadt, Germany. Very intense, high-quality beams of primary and secondary ions will provide to a large scientific community unprecedented new research opportunities in the fields of nuclear, hadron, atomic and plasma physics. Advanced experimental instrumentation will be required, including several experiments comprising high-performance silicon tracking detector systems. This article reviews the concepts of the tracking detectors of the nuclear interaction experiment CBM, the hadron physics experiment PANDA, the nuclear structure and reaction experiments EXL and R^3B, and presents progress with their development.

17th International Workshop on Vertex detectors
July 28 - 1 August 2008
Utö Island, Sweden

*Speaker.

PoS(VERTEX 2008)017

1. The International Research Center FAIR

The new international research center FAIR (Facility for Antiproton and Ion Research) is under realization next to the site of GSI Darmstadt, the german laboratory for research with heavy ions [1, 2]. In a joint effort of currently 14 partner countries, a broad and unique research programme is being prepared. The scientific areas covered include (i) the structure of nuclei far from stability and astrophysics, (ii) hadron spectroscopy and hadronic matter, (iii) compressed nuclear matter, (iv) high energy density in bulk matter, and (v) quantum electrodynamics, strong fields, and ion-matter interactions. The planned advancements are based on the availability of very intense, high-quality beams of primary and secondary ions, including rare and radioactive isotopes, over the full mass range from protons to uranium, and of beams of antiprotons, all provided in a wide range of energies.

The facility is schematically shown in Fig. 1. Its central element is the double-ring heavy-ion synchrotron SIS-100/300 of about 2000 m circumference. The existing accelerator installations of GSI serve as injectors. The HESR is a high-energy storage ring for antiprotons. Ions, both stable and radioactive, as well as low-energy antiprotons are collected, pre-cooled, and stored in the CR, RESR, and NESR storage rings. The facility is designed for an efficient, parallel operation of up to four research programmes with both in-ring and fixed-target experiments at various beam extraction lines.

The official start of the FAIR project was celebrated at GSI on November 7, 2007, with the signature of the memorandum of understanding by the member states' representatives. The FAIR GmbH, a limited liability company after german law that will oversee the construction and will operate the facility, is expected to be established in 2009. In the course of a three-stage construction phase, first experiments are planned to take place in the year 2012. Full operation of FAIR is aimed at for the year 2016.

2. Silicon Tracking Detector Systems for experiments at FAIR

2.1 The CBM Experiment

A comprehensive research programme on nucleus-nucleus collisions will be conducted at FAIR by the Compressed Baryonic Matter (CBM) experiment [3, 4]. The aim is to investigate the QCD phase diagram at highest net baryon densities and moderate temperatures, complemetary to the heavy ion programmes at RHIC and at ALICE/LHC that research on "big bang" physics, i.e. at low densities and high temperatures. Of particular interest are the expected first order phase transition from partonic to hadronic matter, ending in a critical point, and modifications of hadron properties, e.g. their masses, in the dense medium as a signal of chiral symmetry restoration. High-density nuclear matter, only little explored so far, is supposed to exist in neutron stars and in the centres of core-collaps supernova explosions. In the laboratory, it can be created in the reaction volume of colliding relativistic heavy ions. The baryon density and the temperature of the fireball reached in such collisions depend on the type of the collision system and the beam energy. Different states and phases of strongly interacting matter may be studied by colliding various nuclear beams on different targets and scanning the beam energies. Unique possibilities for such studies will open up at FAIR. With projectile energies between 10 and 45 GeV/nucleon, corresponding

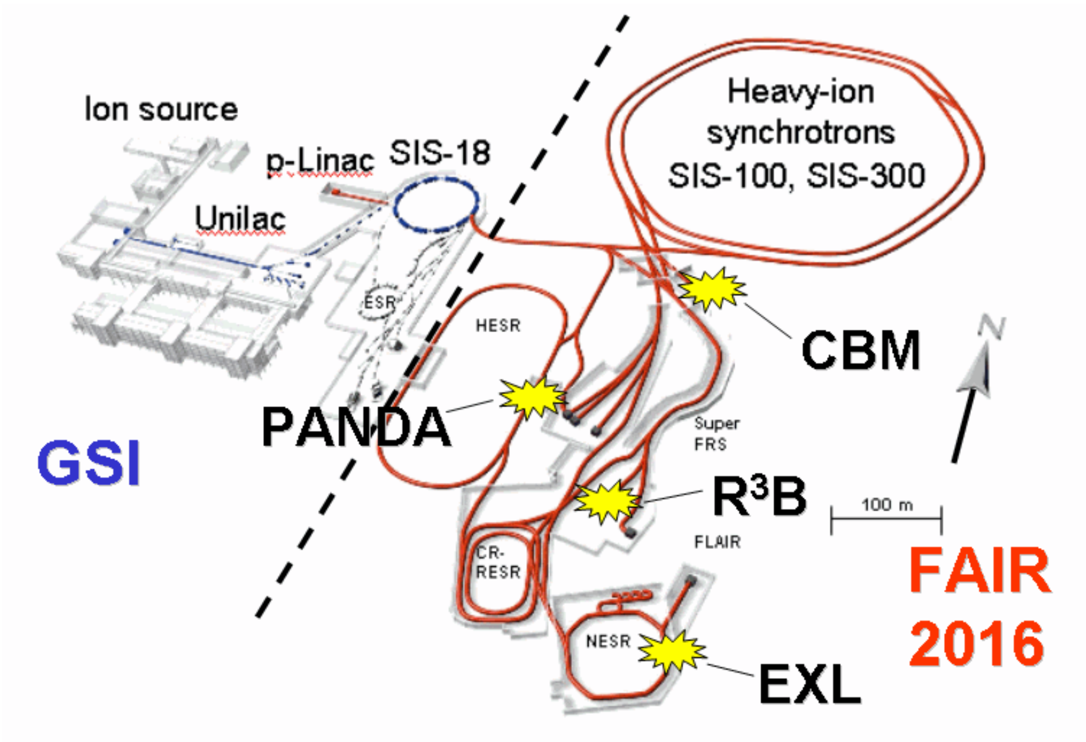

Figure 1: The future FAIR facility with its accelerators and beam lines next to the site of the GSI Laboratory in Darmstadt, Germany. The locations of the experiments discussed in this article are indicated.

to 4.5 - 9.3 GeV centre-of-mass energy per nucleon pair, its accelerators SIS-100/300 will provide intense beams in the range where the highest net baryon densities, up to about 10 times that of ground state nuclear matter, are predicted by transport calculations. Baryon densities of up to about 3 times that of nuclei have already been produced and investigated in heavy-ion collisions at the present SIS-18 accelerator of GSI. The energy range up to 15 GeV/nucleon was pioneered at the AGS accelerator at BNL. With the CBM programme being prepared, renewed interest in this field led to the planning of new programmes to connect to results obtained at the AGS and in the SPS heavy ion programme at CERN. At RHIC/BNL, "low-energy" beams (5-15 GeV/u) will be provided [5, 6]. At JINR Dubna, the NICA [7] accelerator facility has been proposed. The collision rates are expected to be rather low. Measurements will focus on bulk particle production. The full programme including rare probes will be the task of CBM at FAIR.

The planned CBM experiment is schematically shown in Fig. 2. Two detector configurations are being evaluated for electron-hadron and muon-hadron measurements. Both may be realized at different stages. They have in common a low-mass silicon tracking system (STS) [8], the central detector to perform charged-particle tracking and high-resolution momentum measurement. Its concept and development is outlined in the following paragraph. Combined with an ultra-thin micro-vertex detector (MVD) based on monolithic active pixels (for a detailed discussion see M. Deveaux et al. in these proceedings [9]), it will be installed in the gap of a dipole magnet in short distance downstream of the target, typically a gold foil of 250 μm thickness corresponding to 1% nuclear interaction length. In the electron-hadron configuration, the CBM experiment com-

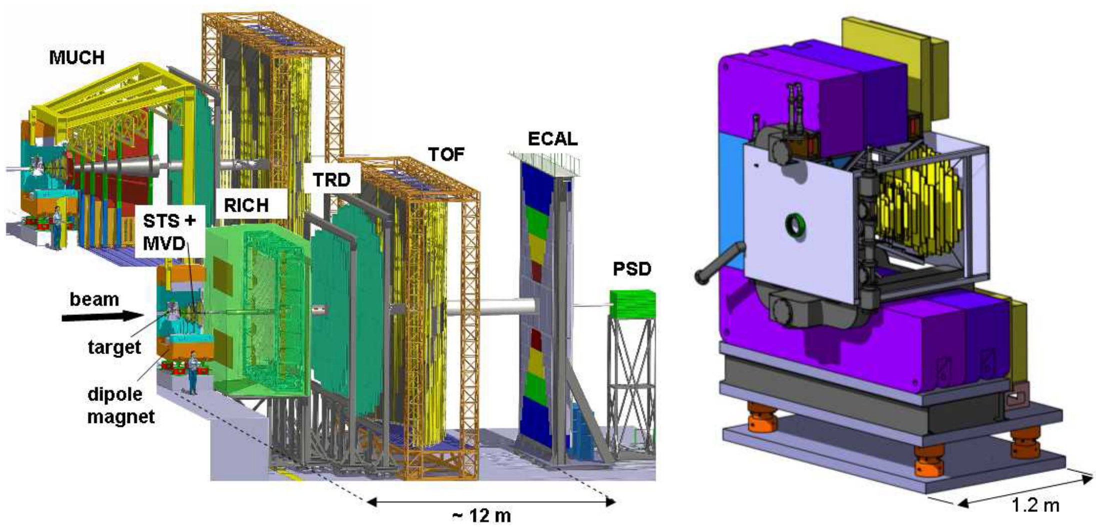

Figure 2: Left: The CBM experiment shown in the electron-hadron configuration (front) and muon configuration (back). Right: Engineering study of the eight-station Silicon Tracking System installed in a thermal enclosure in the 1 T dipole magnet.

prises a ring imaging Cherenkov (RICH) detector downstream of the magnet to identify electron pairs from vector meson decays. Transition radiation detectors (TRDs) provide charged particle tracking and the identification of high energy electrons. Hadron identification will be realized in a time-of-flight (TOF) system built from resistive plate chambers (RPC). An electromagnetic calorimeter (ECAL) will identify and measure the energies of electrons and photons. The projectile spectator detector (PSD) is a calorimeter that determines the centrality of the collisions. In the muon-hadron configuration of the experiment, the RICH detector system is replaced by a compact active absorber system (MUCH). Vector mesons are detected via their decays into muon pairs. Hadrons can be measured with the absorbers moved out. A particular feature of the experiment will be its data acquisition and trigger concept. It is based exclusively on self-triggering front-end electronics that time-stamps the detector signals and sends them to a fast computing farm where event building and high-level trigger generation is performed. This concept is required by the high interaction rates of up to 10 MHz imposed by the physics programme with rare probes, e.g. charm production near threshold.

The CBM silicon tracking system is illustrated in Figs. 2 and 3. Eight planar tracking stations of about 3.5 m^2 total active area will be installed in a 1 T dipole magnetic field. Their task is to efficiently reconstruct the up to 1000 charged tracks that are typically created in 25 GeV/u Au+Au collisions, at rates up to 10 MHz. The detector system therefore has to fulfill three key requirements: (i) its readout has to be dead-time and pile-up free with capturing the hit information at that rate, (ii) its construction must be of low mass to achieve a momentum resolution of about 1% at typical particle momenta of 1 GeV/c, and (iii) its detectors have to be radiation hard. Even though pixel detectors would be the preferred solution for resolving the high-density particle hits, the mass involved with the front-end electronics and its cooling infrastructure in the aperture of the detector would result in a too low momentum resolution if state-of-the-art pixel assemblies as applied in current LHC experiments are considered. New technologies, such as “3D” assembled thinned CMOS chips on thinned detectors, may open up new possibilities and could be integrated into the CBM tracker at a later time. The development of a pixel detector for the PANDA micro vertex detector is followed up closely. The activities for CBM focus instead on the application of silicon microstrip detectors and their assembly into low-mass ladder-like modules that build up the tracking stations. The central idea is to arrange the front-end electronics outside of the tracker's aperture. Inside, only the sectors of single or chained silicon microstrip detectors and very low-mass microstrip aluminum-kapton readout cables remain mounted on a very light carbon fibre support frame. The cables link every strip to its readout channel of the front-end board and may have lengths up to 50 cm. About 1000 detectors will be required with overall about 1.5 million readout channels. The detectors are 300 μm thick, about 6 cm wide and double-sided with 1024 ac-coupled strips of about 60 μm pitch per side. They feature a 15 degree stereo angle between front- and back side strips and involve one or two second metal layers. Detectors with different strip lengths will be required, ranging from 1 cm in regions with high track densities to 6 cm in less exposed detector regions. Detailed simulation studies with the CBM code of the FAIRRoot virtual Monte Carlo framework on the tracking performance of such a detector system have demonstrated high reconstruction efficiency (approx. 97%) and a momentum resolution in the targeted range (approx. 1.5%). A cellular automaton algorithm and a Kalman filter were used to resolve the true hits from the large number of combinatorial hit points. Special versions of the code are being optimized for particular fast computing speed on many-core processors [10].

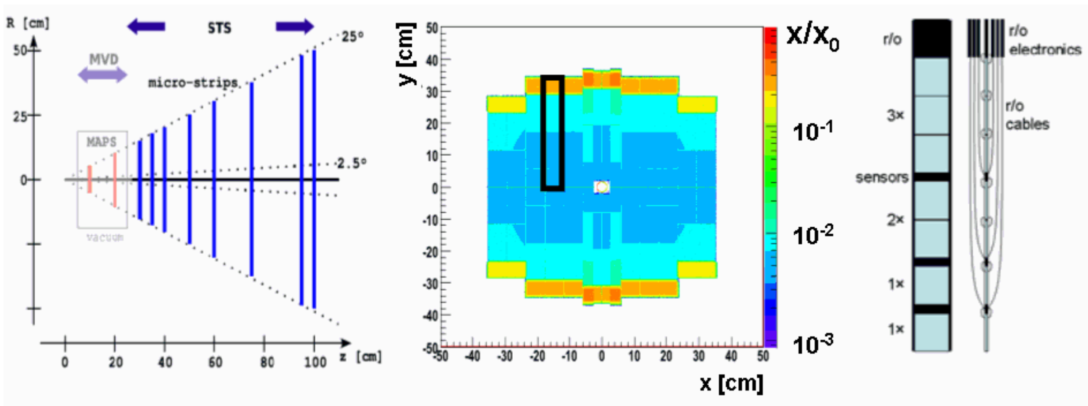

Figure 3: Concept of the CBM silicon tracking system STS. Left: 8 microstrip tracking stations, aperture $\pm$ 25 degrees. Middle: An STS station and its material budget as studied in tracking simulations. The position of a detector module is indicated. Right: A detector module, building block of a tracking station.

Silicon microstrip detectors compatible with this detector concept have been developed in cooperation of the CBM group at GSI and the CIS Research Institute for Micro Sensors and Photovoltaics, Erfurt, Germany [11]. Wafer CBM01, shown in the left photograph of Fig. 4, focussed on exploring the detector topology. Its main detector and smaller test structures have been used for laboratory and first in-beam experiments. A second wafer CBM02 has been produced addressing the radiation hardness of the detectors with different biassing technologies, inter-strip insulations, and doping concentrations. Detailed device and process simulations accompany the detector design. The expected 1-MeV $n_{equiv.}$ fluence for 6 years of detector operation ranges from few times 10^{13} cm^{-2} in the outer parts of the tracking stations up to 10^{15} cm^{-2} in the most exposed regions

Figure 4: Left: 4” wafer from CIS, Erfurt, Germany, with double-sided microstrip detector prototypes CBM01. Middle: First test system comprising CBM01 detectors and n-XYTER front-end electronics. Right: First CBM module demonstrator operated in the SVD-2 experiment at IHEP, Protvino, Russia.

close to the beam line and in the last station facing the MUCH detector system. The engineering of the silicon tracking system will include a thermal enclosure and cooling infrastructure to operate the detectors at temperatures several degrees below 0 °C.

A first system test of CBM microstrip detectors connected to self-triggering front-end electronics has been performed at GSI in autumn 2008 and demonstrated the validity of the concept. The middle photograph of Fig. 4 shows a two-board setup connected to n-XYTER [12] readout chips that was characterized with 2.5 GeV protons on a dedicated GSI test-beam line. Based on the architecture of the n-XYTER chip, developed in a different project, the CBM collaboration plans to develop a new CBM-XYTER chip tailored to the requirements of the experiment. In particular, the power dissipation must be reduced and the radiation hardness increased.

The development of the CBM module prototype is the subject of the CBM-MPD Silicon Tracker Consortium [13], established by GSI and JINR Dubna as a joint R&D activity for the CBM experiment at FAIR and the MPD experiment at NICA. The central task of this effort are the construction of the lightweight support structure, and of the ultra-thin micro-line readout cables. The mechanical support is based on a thin but very stiff carbon fibre skeleton with a base element of square pyramidal shape, similar to the development made in St. Petersburg, Russia, for the ALICE inner tracking system [14] but arranged in a planar geometry. Several pre-prototypes of short and long readout cables have been produced at SE SRTIIE Kharkov, Ukraine, with a 14 μm thick metal layer on 10 μm polyimide. A first demonstrator tracking module with a CBM01 test detector read out through tab-bonded Al-Kapton microcables, shown in Fig. 4, has been successfully operated in November, 2008, in the beam tracker of the SVD-2 experiment at IHEP Protvino [15] where it contributed to the physics data taking of the experiment.

For 2009, the CBM silicon tracking project aims at developing the demonstrator of a larger ladder, including a high-density front-end board with up to 8 n-XYTER chips. The assembly steps of the double-sided structure will be elaborated including the development of necessary tooling. The measurements will focus on the electrical integrity of the detector system to perform particle detection with suffuciently high signal-to-noise ratio. A self-triggering reference tracking telescope for systematic in-beam tests of the forthcoming CBM components is under construction. Together with partners from Finland, further activities will explore 150 μm thick single-sided microstrip detectors for areas where highest radiation tolarance will be required.

2.2 The PANDA Experiment

The PANDA (AntiProton ANnihilations at DArmstadt) experiment [16, 17] is a next-generation hadron physics experiment. Planned at the HESR storage ring, it is being designed to investigate the interactions of cooled antiproton beams of 1.5 GeV - 15 GeV energy with various internal targets, in particular gas jets/pellets of hydrogen or heavier elements. The interaction rates will be as high as 20 MHz. The primary physics goals include precision spectroscopy of charmonium states, establishment of gluonic excitations, the study of modifications of meson properties in the nuclear medium, and precision gamma-ray spectroscopy of single and double hypernuclei.

The proposed detector is schematically shown in Fig. 5. It combines a forward dipole spectrometer with a solenoid field region around the target. Despite the strong forward boost of a fixed-target experiment, coverage in both the forward and backward direction is crucial for certain types of reactions where low-energy pions and kaons may be emitted in 4π. Angles below 10° in the forward direction will be covered by a dipole spectrometer equipped with drift chamber tracking, particle ID layers as well as electromagnetic and hadronic calorimetry. The central superconducting solenoid surrounding the target has a maximum field of 2T. Photons will be measured in an electromagnetic calorimeter of high granularity, built from $PbWO_4$ crystals read out with avalanche photo diodes. Particle identification will be performed with a Cherenkov detector of DIRC type in the barrel structure, augmented by a forward RICH and time-of-flight measurements. In the barrel region, the outer part of the tracking section will consist of 15 double layers of straw detectors. As an alternative for the central tracking, a TPC with GEM readout is discussed. Inside of the central tracker, just around the beamline, a micro-vertex detector (MVD) will be used to give an accurate account of the particle tracks very close to the interaction region.

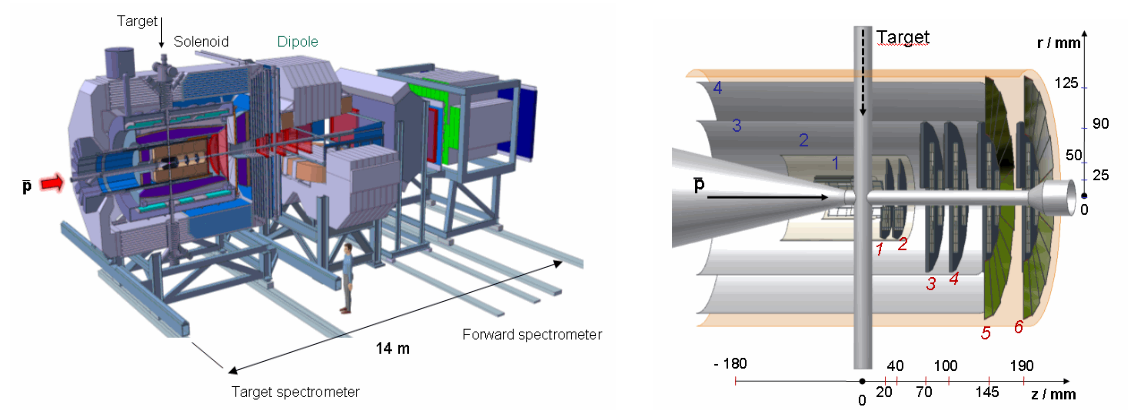

Figure 5: Left: The PANDA experiment. Right: The PANDA micro vertex detector MVD.

For many of the physics goals, an identification of D-mesons via the detection of a secondary vertex with a decay length of the order of 100 μm is essential. The MVD will comprise four barrel layers and six forward discs, composed of silicon pixel and strip detectors. The layout, shown in the right part of Fig. 5, allows the measurement of at least five space points in the forward direction, and four space points in the barrel region. A hybrid pixel solution was chosen for the inner two barrels and the inner two forward discs, representing about 0.15 m^2 area. In particular the pixel detectors shall provide a fast, self-triggering readout. Modular ladder-like structures are planned that allow them being mounted at the smallest possible inner radius around the beam pipe. The larger area of the outer two barrels and the outer two discs are planned to be built from double-sided microstrip detectors, covering an area of about 0.6 m^2. A typical barrel microstrip detector has dimensions of 6 cm by 3.5 cm and a thickness of 200 μm, with orthogonal strips of 50-100 μm pitch. Detectors of the discs have a wedge shape. Radiation hardness as realized in the current LHC experiments, i.e. fluences of up to several times 10^{14} $n_{equiv.}$ cm^{-2}, will suffice to run the detectors for the full PANDA lifetime.

The development of the detector system is being performed with simulation studies using the PANDARoot code of the FAIRRoot framework, engineering studies including mockups of a possible mechanical realization around the pellet target/beam pipe infrastructure, as well as detector development for the hybrid pixel and microstrip components.

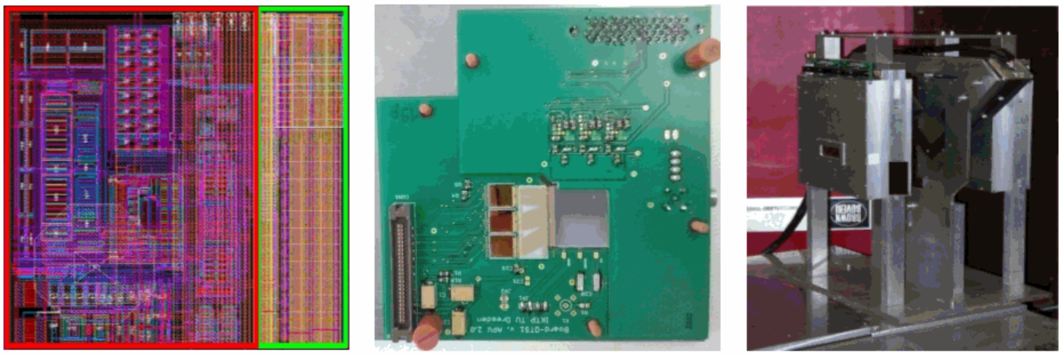

Figure 6: Left: Layout of the 100 by 100 μm^2 pixel detector cell of the first PANDA TOPIX prototype chip. Middle: Test board for microstrip detectors of PANDA based on the APV readout chip. Right: Telescope for in-beam characterization at the electron accelerator ELSA, University of Bonn.

A first prototype of a hybrid pixel detector readout chip, TOPIX [18], has been designed and produced in .13 μm CMOS technology. The chip features an array of 32 pixels of 100 by 100 μm^2 size. The layout of a cell, shown in Fig. 6, illustrates in the right part a block for digital data treatment, allowing for sufficient buffering to operate without trigger, and on the left an analog part including a time-over-threshold circuit to retain some energy information of the particle hit. The circuit was tested for electrical functionality and radiation damage tolerance. Exposures to a neutron flux of several 10^{14} 1-MeV $n_{equiv.}$/cm^2 were performed, corresponding to 10 years of PANDA operation. The final assembly of back-thinned readout chips is foreseen to be made via low-mass bump bonding or novel "3D" assembly technologies through a bond pad, indicated in the figure as well, to epitaxial sensors of 100 μm thickness or less. Prototypes of the sensors are being developed together with ITC, Trento, Italy.

The microstrip detectors are intended to be 200 μm thick, double-sided with orthogonal strips of 50 - 100 μm pitch. A typical barrel detector may be 6 cm wide with strips of 3.5 cm length. Laboratory activity has been started with a test board shown in Fig. 6, developed around the APV 25 chip and double-sided test detectors from ITC coming from the AMS project. As the application in the PANDA MVD will finally require self-triggering front-end electronics, synergy with the development of XYTER ASICs for the CBM experiment is planned. This may also include the development of the microstrip sensors.

2.3 NUSTAR Experiments

The international nuclear structure and astrophysics community NUSTAR [19] plans to develop, construct, and operate a new rare-isotope facility at FAIR. It will comprise a super-conducting fragment recoil separator (Super-FRS) and three experimental areas, the low-energy branch, high-energy branch, and ring branch. In the following, focus is put on the reaction experiment EXL at the storage ring NESR, and the reaction experiment with high-energy rare-ion beams R^3B.

2.3.1 The EXL Experiment

The EXL (EXotic nuclei studied in Light-ion induced reactions) experiment [20, 21] aims at investigating light-ion induced direct reactions in inverse kinematics by using a universal detector system built around the internal target station at the new experimental storage ring NESR. Secondary beams of unstable nuclei are produced by fragmentation or fission reactions, separated in the Super-FRS fragment separator, and then accumulated in the Collector Ring (CR), from where they are transferred into the NESR ring where the measurements are performed with the EXL detector. The ions can be decelerated down to energies of a few MeV to investigate transfer and capture reactions.

The experimental setup is schematically shown in Fig. 7. The cooled radioactive-ion beam passes a gas-jet target while circulating in the storage ring. Recoiling target ions, e.g., protons or α particles, are detected by the recoil detector surrounding the target. Particles are tracked by position sensitive silicon microstrip detectors, and their energy is measured in Si(Li) or scintillation detectors. In the forward direction, charged ejectiles and neutrons are measured by detectors placed at small angles around the beam pipe. Heavy fragments can be analyzed by using the first arc of the storage ring as a magnetic spectrometer. The experimental approach thus allows a kinematically complete measurement of the reaction products. It is complementary to the R^3B experiment since it covers the low-momentum transfer part of the scattering processes, which cannot efficiently be measured in R^3B.

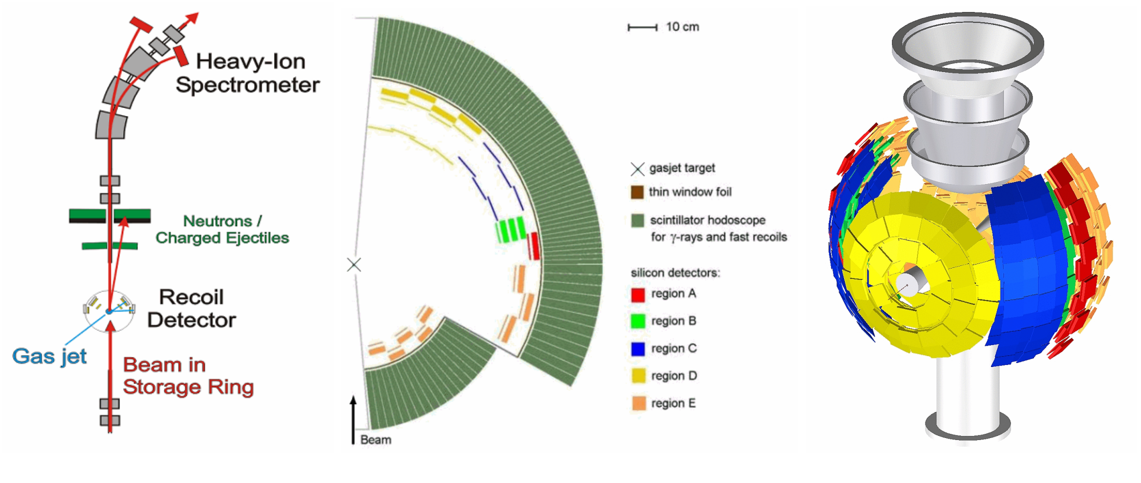

Figure 7: Left: The EXL experiment built into the NESR storage ring. Middle and right: Gas-jet target, and recoil silicon and scintillator detectors.

It is foreseen to separate two regions of the setup with different vacuum conditions by a thin window. The inner "high vacuum" part will house the silicon particle array which will be bakeable to temperatures in the vicinity of 130 °C in order to reach a vacuum of at least 10^{-8} - 10^{-9} mbar. The outer "low vacuum" part of the detector chamber will house the array of scintillation detectors, which is dedicated to detect the gamma-rays as well as the residual energy of fast recoil particles punching through the silicon detectors. A vacuum of about 10^{-5} mbar will be sufficient for that part of the scattering chamber.

For the recoil detector, two nearly spherical silicon layers are foreseen with a total area of about 3 m^2.The inner layer will provide particle track points in less than 100 μm thick double-sided orthogonal silicon microstrip detectors with a spatial resolution of better than 100 μm in x and y, and an energy resolution of 30 keV. It is comprised of 300 detectors with typical dimensions of 9 cm by 9 cm. The outer layer will determine energy loss with 30 keV resolution in 300 μm thick double-sided orthogonal silicon microstrip detectors and spatial resolution better than 500 μm in both coordinates. It is built from 120 detectors of 9 cm by 9 cm size. There are only standard requirements on the radiation hardness, i.e. up to fluences of around 10^{13} $n_{equiv.}$ cm^{-2}. In several areas, 9 mm thick lithium-drifted silicon detectors are foreseen behind the second microstrip detector layer to optimize the energy resolution. A scintillator hodoscope consisting of about 1500 individual crystals, built of CsI or other scintillator material, will surround the silicon tracker 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.

2.3.2 The R^3B Experiment

The aim of the international collaboration R^3B (Reaction experiment with Relativistic Radioactive Beams) [22, 23] is to develop and to construct a versatile reaction setup with high efficiency, acceptance, and resolution for kinematically complete measurements of reactions with high-energy radioactive beams. The setup will be located at the focal plane of the high-energy branch of the Super-FRS, thus taking full advantage of the characteristics of radioactive beams produced by the in-flight separation method including the highest possible transmission to the target.

The experimental setup is illustrated in Fig. 8. The incoming ions are identified on an event-by-event basis and tracked onto the reaction target enabling a simultaneous use of beams composed of many isotopes. Two operation modes are foreseen, one for large-acceptance measurements of heavy fragments and light charged particles, and another for high resolution momentum measurements using a magnetic spectrometer. A large-acceptance super-conducting dipole magnet together with tracking detectors serves for the momentum analysis of the heavy fragments. The large gap of the dipole allows charged particles and neutrons of projectile rapidity emitted from excited fragments to be detected behind the magnet by drift chambers and a RPC-based neutron detector at zero degrees, respectively, which provide excellent position and time resolution. The target area, with the possibility of inserting a liquid or frozen hydrogen target, is surrounded by a silicon vertex tracker inside a combined charged-particle and gamma calorimeter.

The silicon tracker will sample with 3 barrel layers the tracks of outgoing particles from radioactive beam reactions on the target. The detector comprises some 80 microstrip detectors of about 5 cm by 7 cm size, covering about 0.2 m^2 area. The detectors are double-sided with orthogonal strip pattern, read out from the same detector edge, thus involving a double-metal routing layer on one side. The strip pitch is 100 μm or smaller. Detectors of both 100 μm (inner layer) and 300 μm thickness (outer layers) will be required. Like in the EXL setup, there are only standard requirements on the radiation hardness. The collaboration investigates whether thin monolithic pixel detectors like the INMAPS [24] technology of RAL may be applicable in the inner layer.

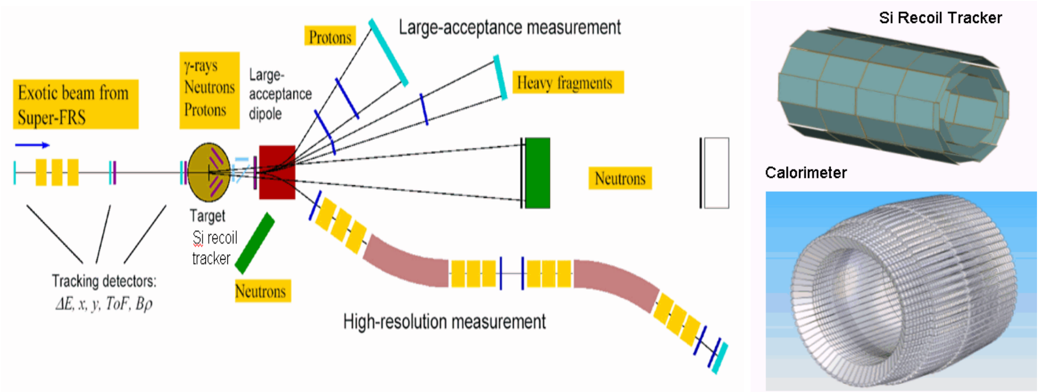

Figure 8: Left: The R3B experiment at the super fragment separator. Right: Representation of the target-recoil silicon detector and calorimeter systems.

2.3.3 Silicon detector development for EXL and R^{3}B

First prototypes of double-sided silicon microstrip detctors have been produced in a joint effort of the EXL and R^{3}B workgroups in collaboration with PTI St. Petersburg, Russia. Figure 9 shows a photograph of a 4" wafer of 300 μm thickness with different detectors of orthogonal segmentations between 16 by 16 and 256 by 256 dc-coupled strips of 100 and 300 μm pitch. A test stand has been set up at GSI that allows to operate the prototype detectors under vacuum of around 4×10^{-7} Torr. The energy resolution has been studied by detecting signals from an ^{241}Am source with discrete CATSA pre-amplifiers through a CAMAC/VME based trigger and data acquisition system [25]. A beam test with a first EXL/R3B module demonstrator is planned for the year 2009.

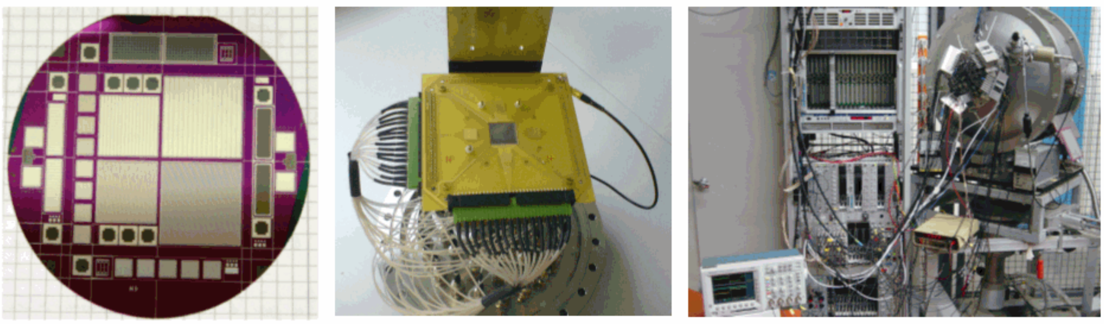

Figure 9: Left: First double-sided microstrip detector prototypes developed for the EXL and R^{3}B experiments. The 4" wafers were produced at PTI, St. Petersburg, Russia. Middle: A detector mounted on a GSI test board. Right: Test stand at GSI for detector operation in a vacuum chamber.

3. Summary

Key figures of the silicon tracking detector systems under design and development at FAIR are summarized in the following table.

	CBM	PANDA	EXL	R^3B
layers	8 planar stations	4 barrels, 4 forw. discs	2 spheres	3 barrels
area	3.5 m^2	0.6 m^2 (strips) 0.15 m^2 (pix.)	3 m^2	0.2 m^2
magnetic field	1 T dipole	2 T solenoid	none	none
detector technology	2-sided strips, 1-sided strips	2-sided strips, hybrid pixels	2-sided strips	2-sided strips
sensors	300 μm thick; 6 cm wide; 60 μm pitch; AC coupled; 15° stereo	200 μm thick; 6 cm wide; 100 μm pitch; orthog. strips; squared pixels	100, 300 μm thick; 9 cm wide; resolution 100 μm and 30 keV	100, 300 μm thick; 5 cm wide; 100 μm pitch; orthogonal
readout channels	1.5×10^6	7×10^5 (strips) 13×10^6 (pix.)	1×10^5	1×10^5
front-end readout	XYTER	t.b.d., TOPIX	t.b.d.	t.b.d.
interaction system	p-A, A-A (typ. Au-Au)	$\bar{p}$-H, $\bar{p}$-A	A-A	p-A, A-A
beam energy	$\leq$45 GeV/u	1.5 - 15 GeV	740 MeV/u	0.2 - 2 GeV/u
interaction rate	$\leq$ 10 MHz	$\leq$ 20 MHz	$\leq$ 1 MHz	0.1-10^4 Hz
tracks/event	$\leq$ 1000	< 100	< 100	< 100
radiation tolerance [1 MeV n/cm^2]	10^{13}-10^{15}	10^{14}	< 10^{13}	< 10^{13}
special	high channel density, fast self-triggering r/o, low-mass; separate MVD	fast self-triggering r/o; thin hybrid pixel detectors	in-ring experiment: Det. operation in ultra high vacuum	calorimeter with inner silicon tracking

Acknowledgements

The speaker, coordinator of the CBM silicon tracking project, wishes to thank K.T. Brinkmann (PANDA Collaboration), P. Egelhof (EXL Collaboration) and R.C. Lemmon (R^3B Collaboration) for material provided for this overview. The development of components for some of the discussed silicon tracking systems (CBM, PANDA) receives partial support from the EU-FP7 Project HadronPhysics2 [26].

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