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The control system of the polarized internal target of ANKE at COSY

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Abstract

The polarized internal target for the ANKE experiment at the Cooler Synchrotron COSY of the Forschungszentrum Jülich utilizes a polarized atomic beam source to feed a storage cell with polarized hydrogen or deuterium atoms. The nuclear polarization is measured with a Lamb-shift polarimeter. For common control of the two systems, industrial equipment was selected providing reliable, long-term support and remote control of the target as well as measurement and optimization of its operating parameters. The interlock system has been implemented on the basis of SIEMENS SIMATIC S7-300 family of programmable logic controllers. In order to unify the interfacing to the control computer, all front-end equipment is connected via the PROFIBUS DP fieldbus. The process control software was implemented using the Windows-based WinCC toolkit from SIEMENS. The variety of components, to be controlled, and the logical structure of the control and interlock system are described. Finally, a number of applications derived from the present development to other, new installations are briefly mentioned.

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Keywords: Programmable logic controllers; SCADA system; PROFIBUS DP; Polarized atomic beam source; Lamb-shift polarimeter

1. Introduction

Future measurements with the magnet spectrometer ANKE [1] at the accelerator ring COSY (Jülich, Germany) [2] involve few-nucleon reactions, where both beam and target particles are polarized. For this purpose, a polarized **A**tomic **B**eam **S**ource (**ABS**)[3] has been developed [3]. It provides intense beams of up to $\sim 7 \times 10^{16}$ hydrogen or deuterium atoms per second that will be injected into the storage cell of the **P**olarized **I**nternal **T**arget (**PIT**). The nuclear polarization of the ABS beam or of a sample of atoms, extracted from the storage cell, is measured with a **L**amb-**S**hift **P**olarimeter (**LSP**) [4]. The 3D CAD drawing in Fig. 1 shows the ABS and the LSP in their future position at the target chamber of the ANKE setup within the COSY tunnel.

From the beginning, special attention was devoted to the control system. It has to facilitate experimental tests and studies of operational parameters of ABS and LSP and it has to support and to control the routine operation the target as well. Most important, the control system has to ensure stable and reliable operation, and at the same time it has to enable a high degree of flexibility and to allow for extensions during the development phase.

The front-end equipment, to be controlled, comprises about 200 components from different vendors (vacuum pumps and gauges, power and rf supplies etc.). With respect to control, this constitutes a medium-sized, but extremely heterogeneous system with about 800 process

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[3]Acronyms, not commonly known, are once given in bold-face together with the full term at the first occurrence.

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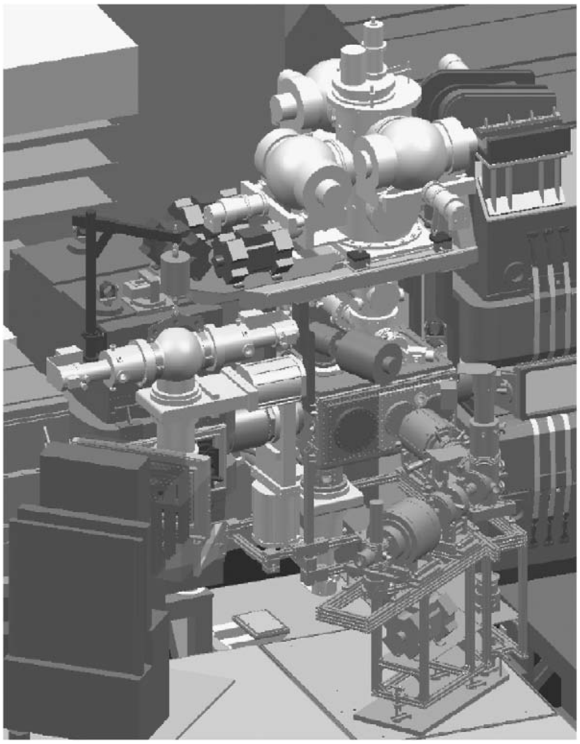

Fig. 1. 3D CAD drawing of the polarized atomic beam source (vertical) and the Lamb-shift polarimeter (horizontal, with the 60° deflector) at the ANKE-target chamber in front of the central spectrometer dipole magnet (right-hand side).

signals and about 30 serial interfaces, used for the more sophisticated devices.

Control systems for accelerators or physics experiments are in general dominated by home-made systems, although **PLC**s (**P**rogrammable **L**ogic **C**ontrollers) and other industrial equipment are increasingly being employed. Especially at CERN, there is a strong movement towards global industrial control solutions [5,6]. The main motivations for this recent development are:

- low price caused by mass market,
- robustness,
- long-term availability and support from producers,
- powerful development tools, and
- standard interfaces.

Because of the above mentioned reasons, industrial control technologies are employed in the PIT control system. The selected technologies include S7-300 PLCs,[4] the PROFIBUS[5] **DP** (**D**ecentralized **P**eriphery) as a fieldbus, and the Windows based **SCADA** (**S**upervisory **C**ontrol **A**nd **D**ata **A**cquisition) [5] system WinCC (see footnote 4).

Section 2, in a schematic way, describes the ABS (Section 2.1), the LSP (Section 2.2), and a stepper-motor positioning system for components installed in the ANKE-target chamber (Section 2.3). In Section 3, the criteria for the selection of the control-system components are discussed. Section 4 presents the logical structure of the system controlling the ABS (Section 4.1), the LSP (Section 4.2), and the separate system used for the positioning setup (Section 4.3). Section 5 describes the physical structure of the control systems, the implemented modules, and the connection of the front-end devices to the PLCs. A short Section 6 gives an overview of the additional hard- and software, developed for studies of operational parameters. Conclusions, further applications of components of the present control system, and an outlook are found in Section 7.

[4]A product of Siemens AG, Automatisierungs- und Antriebstechnik, D-90475 Nürnberg, Germany.

[5]International standard IEC 61158.

2. Components in the setup to be monitored and controlled

2.1. Components of the polarized atomic beam source

The ABS produces a beam of polarized H or D atoms, which are injected into a T-shaped windowless storage cell. The stored beam, circulating in the COSY ring, interacts with the target gas. A schematic drawing of the ABS, containing only those components which are embedded in the control system, is displayed in Fig. 2.

Controlled flows[6] of molecular hydrogen or deuterium gas (about 1 mbar·l/s) and a small admixture of oxygen (10^{-3} to 10^{-2} mbar· l/s) are introduced into the inner tube of the dissociator which is cooled by a mixture of ethanol and water using a refrigerator.[7] In a plasma discharge, fed by a 13.56 MHz rf generator with an adapter network,[8] the gas molecules are dissociated into atoms. The measured coolant flow[9] and its input and output temperatures yield the applied cooling power. The typical gas pressure in the discharge tube, p_{diss}, is about 1 mbar and is monitored by a capacitance vacuum gauge.[10] Appropriate beam parameters are achieved by cooling the nozzle to about 60 K via a cryogenic cold head,[11] supplied by a He compressor.[12] The cold head temperature T_{Si} is monitored by a silicon diode.[13] The nozzle temperature is stabilized within ±0.5 K by a **PID** (**P**roportional-**I**ntegral-**D**erivative) control net-

[6]Gas-flow controllers in the modular system 146C, MKS Instruments Deutschland GmbH, D-81829 München, Germany.

[7]ULTRA-KRYOMAT RUL-80-D, Lauda Dr. R. Wobser GmbH, D-97912 Lauda-Königshofen, Germany.

[8]HF-Generator PFG 600 RF with tuning network PFM 1500 A, Hüttinger Elektronik GmbH, D-79110 Freiburg, Germany.

[9]Full-metal flow meter KDM-VDYYAYYLC, Kobold Messring GmbH, D-65179 Hofheim, Germany.

[10]Baratron gauge in the modular MKS system 146C (see footnote 6).

[11]Single-stage cold head RGS 120, Leybold Vakuum GmbH, D-50968 Köln, Germany.

[12]The cold head and the Leybold cryogenic pumps, used in the setup, are connected to Leybold (see footnote 11) compressors RW 4000, RW 6000, COOLPAK 4000, and COOLPAK 6000.

[13]Type D connected to a Leybold (see footnote 11) voltage-to-temperature converter LTI 10. Being no longer produced, the LTI 10 now are replaced by LakeShore Temperature Monitors, model 211-230 (distributor: Cryophysics GmbH, D-64293 Darmstadt).

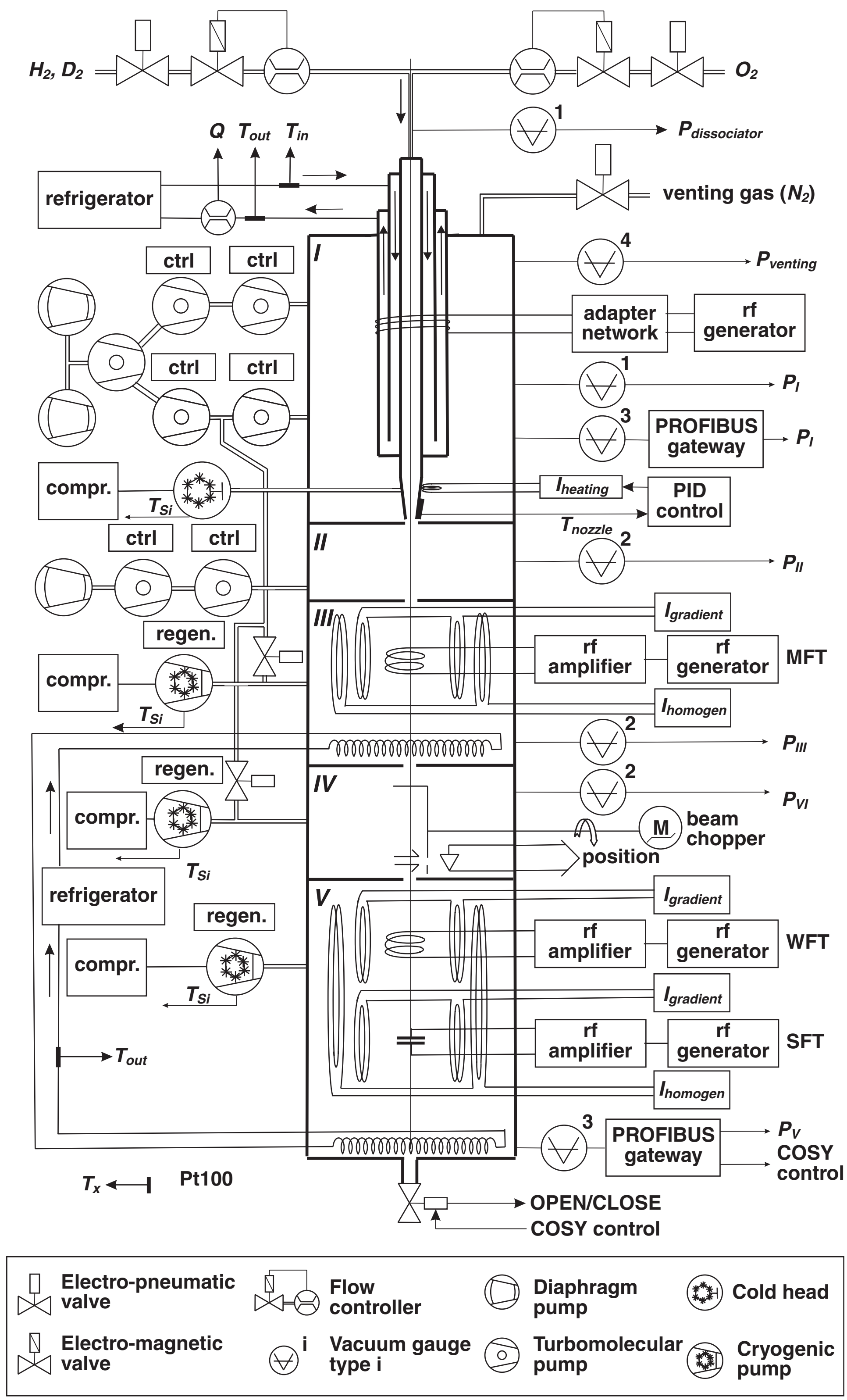

Fig. 2. Scheme of those components of the polarized atomic beam source which are embedded in the control system. (The figure, e.g., does not show the permanent sextupole magnets.) The labels on the vacuum gauges denote their type (1: capacitance/baratron, 2: cold-cathode, 3: combined Pirani/Bayard-Alpert, 4: piezoelectric).

work[14] including a Pt100 resistor for temperature measurement and a heater unit.[15] A **M**edium **F**ield rf **T**ransition (**MFT**) unit,[16] a **W**eak **F**ield rf **T**ransition (**WFT**) unit,[17] and a **S**trong **F**ield rf **T**ransition (**SFT**) unit[18] have been developed [7] to achieve the wanted nuclear polarization of the atomic beam from the ABS. The homogeneous and gradient magnetic fields in the MFT unit, the gradient fields in the WFT and SFT units and their common homogeneous fields are produced by five magnet coils[19] and water-cooled[20] iron yokes. The beam can be chopped by a rotating cylinder with appropriate apertures driven by a stepper motor.[21,22] The chopper position is controlled by a light-emitting and a photo diode.[23] The beam chopper together with a crossed-beam quadruple mass spectrometer[24] have been used to measure the degree of dissociation of the beam from the nozzle [8]. Furthermore, the beam chopper allows one to study the time distribution of the H_1^+ and H_2^+ currents, extracted from the ionizer in the LSP [9].

Essential components in the system are the pumps to achieve the needed vacua in the ABS chambers I–V (Fig. 2). The highest gas load is encountered in chamber I. Two strong turbomolecular pumps[25] are backed by two stages of smaller ones[26] and diaphragm pumps.[27] Chamber II is equipped with a single line of such pumps. Each control unit is included into the control system. The chambers III and IV are pumped by strong cryogenic pumps,[28] supplied by He compressors (see footnote 12), whereas a smaller one[29] is mounted on chamber V. The temperatures of the second stages of the cold heads are monitored by Si diodes (see footnote 13). All cryogenic pumps are equipped with regeneration units,[30] operated by the control system to remove the accumulated gas by predefined heating via the bypass line connecting the cryogenic pumps and one branch of the turbomolecular pumps (Fig. 2).

The pressures p_{I} to p_{V} are monitored by various vacuum gauges. In Fig. 2, label 1 at the gauge symbol denotes a capacitance gauge (see footnote 10), label 2 a cold-cathode gauge,[31] and label 3 a combined Pirani/Bayard-Alpert (hot cathode) gauge.[32] The pressure in chamber V has to be made available to the COSY control system. Only this system is authorized to open the gate valve to the target chamber, when the pressure in chamber V fulfills the COSY-vacuum conditions. An additional piezoelectric gauge[33] in chamber I (labeled 4 in Fig. 2) is used to limit the pressure p_{vent} in the ABS vessel to ~1020 mbar, when the ABS is vented with nitrogen.

2.2. Components of the Lamb-shift polarimeter

The LSP is used to measure the polarization (i) of the atoms in the ABS beam or (ii) of a gas sample extracted from the storage cell. In first case (i), atoms from the vertically mounted ABS are injected into the ionizer, and an electrostatic 90° deflector guides the ions onto the horizontal LSP-beam axis. The configuration of the second case (ii), described here, will be utilized at the ANKE target chamber. In this case, the axes of the storage cell, of the sampling tube, and those of the LSP lie in a common horizontal plane. Fig. 3 shows schematically the LSP components included in the control system.

The beam from the sampling tube is chopped by a rotating wheel, positioned inside the target chamber and driven by a DC motor.[34] The position of the chopper wheel is monitored by the light transmitted through a slit in the rotating wheel (see footnote 23). A home-made module delivers the current for the motor and amplifies the signal from the photo diode, which is used as trigger in measurements with chopped beam. Gas atoms that enter the ionizer are ionized by electrons emitted from a hot filament.[35] Five lenses in the ionizer are used to accelerate the electrons and the produced ions, by appropriate electrostatic potentials U_1^{ion} to U_5^{ion} from individual power supplies.[36] The solenoidal magnetic field of up to 150 mT, required to operate the ionizer in a defined mode [10], is

[14]PID module S7-300, FM 355 C, Siemens AG (see footnote 4).

[15]D.C. power supply Statron 0–30 V/0–2 A, Statron Gerätetechnik GmbH, D-15517 Fürstenwalde, Germany.

[16]Fed by a 10–1000 MHz signal generator TGR 1040, Thurlby Thandar Instruments, and a wideband power amplifier RF001100-10, R.F.P.A. SA (distributor for both units: Telemeter Electronics GmbH, D-86609 Donauwörth, Germany).

[17]Fed by a 0.5–20 MHz function generator FG 100, Grundig AG, D-90766 Fürth, Germany, and by a RF001100-10 amplifier, R.F.P.A. SA (see footnote 16).

[18]Fed by a 9 kHz–2.2 GHz signal generator SML02, Rohde & Schwarz Messgerätebau GmbH, D-87686 Memmingen, Germany, and a wideband power amplifier RF502000-10-bi, R.F.P.A. Sa (see footnote 16).

[19]All fed by bipolar operational power supply/amplifier units Kepco BOP 20-5M (distributor: CompuMess Elektronik GmbH, D-85716 Unterschleißheim, Germany).

[20]Umlaufkühler WK 500, Lauda Dr. R. Wobser GmbH (see footnote 7).

[21]Motorized rotary drive ZRD91M, Vacuum Generators, Hastings TN38 9NN, Great Britain.

[22]Stepper motor power supply UMS 3.5, Iselautomation KG, D-36124 Eichenzell, Germany.

[23]Standard slotted optical CNY28 switch.

[24]Masstorr200, Vacuum Generators (see footnote 21).

[25]TPH 2200 C with control unit TCP 600, Pfeiffer Vacuum GmbH, D-35614 Asslar, Germany.

[26]TMH 260 C with control unit TCP 380, Pfeiffer Vacuum GmbH (see footnote 25).

[27]MD 8, Pfeiffer Vacuum GmbH (see footnote 25).

[28]COOLVAC 3000, Leybold Vakuum GmbH (see footnote 11).

[29]COOLVAC 800, Leybold Vakuum GmbH (see footnote 11).

[30]HU 1, Leybold Vakuum GmbH (see footnote 11).

[31]Component in the modular MKS system 146C (see footnote 6).

[32]HPT 100 with TIC 252 PROFIBUS DP gateway, Pfeiffer Vacuum GmbH (see footnote 25).

[33]APR 250, Pfeiffer Vacuum GmbH (see footnote 25).

[34]Model 16 N 28 207E 201, API Portescap, CH-2301 La Chaux-de-Fonds, Switzerland.

[35]Power supply (0–6.5 V/0–5 A) NTN 35-6.5, F.u.G. Elektronik GmbH, D-83024 Rosenheim, Germany.

[36]Lenses 1 and 4: NCE 1200-25 (0–1200 V/0–25 mA), 2: NCE 3000-20 (0–3000 V/0–20 mA), 3: NCE 3000-10 (0–3000 V/0–10 mA), 5: NCE 6000-5 (0–6000 V/0–5 mA), Knürr AG, D-94424 Arnstorf, Germany.

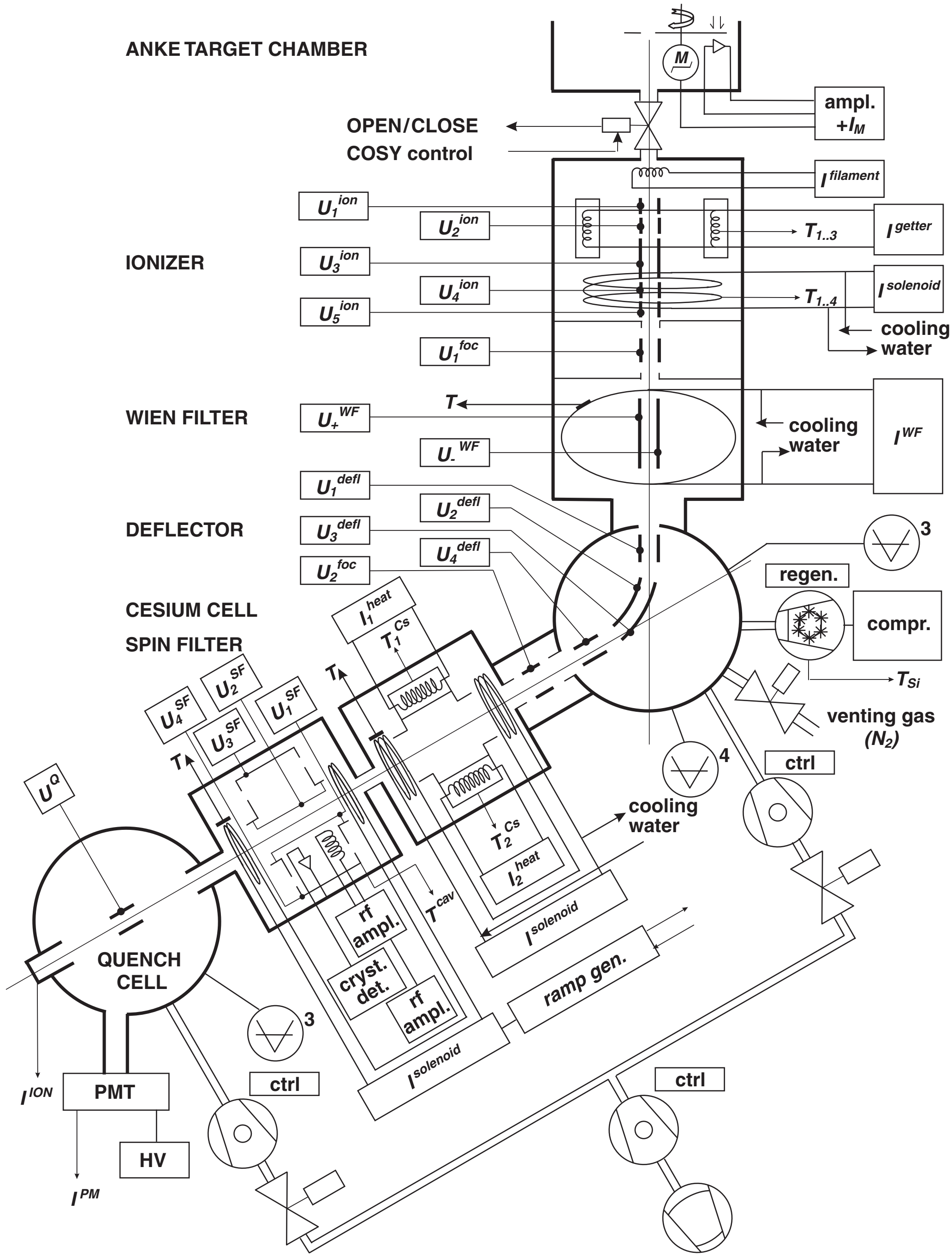

Fig. 3. Scheme of the controlled components of the Lamb-shift polarimeter with beam chopper in the ANKE target chamber, ionizer, Wien filter, 60° deflector, cesium charge-exchange cell, spin filter, and quench chamber. The symbols are explained in the caption of Fig. 2.

produced by a water-cooled hollow-conductor coil.[37] The temperature distribution inside the ionizer is monitored by four thermal resistors[38] that switch off the supply current when a critical temperature is exceeded. The necessary vacuum in the ionizer volume is achieved [9] by a nonevaporable getter pump,[39] activated by heating up to 400 °C.[40] The temperature distribution of the getter material is monitored by three embedded thermocouples.[41]

[37]Power supply HP 6499 C (0–20 V/0–700 A), Hewlett Packard.

[38]Type K252/10%/40 kΩ; EPCOS AG, D-81669 München, Germany.

[39]Assembled from getter cartridges C 500-MK2-ST707, SAES Advanced Technologies S.p.A., I-67051 Avezzano, Italy (distributor: SAES Getters Deutschland GmbH, D-50937 Köln, Germany).

[40]Power supply NTN 1400-65 (0–65 V/0–20 A), F.u.G. Elektronik GmbH, D-83024 Rosenheim, Germany.

[41]2ABI20/400 mm/Tl/MF9F, Thermocoax GmbH, D-22145 Stapelfeld, Germany.

An additional lens, kept[42] at the potential U_1^{foc}, focuses the ions from the ionizer into the Wien filter [11]. Its magnetic field, produced by water-cooled hollow conductor coils[43] together with a perpendicular electric field,[44] are used for mass separation and to adjust the quantization axis of the polarized ions.

Due to space limitations at the ANKE target, the beam has to be bent by 60° behind the Wien filter. In the deflector setup [11], this is achieved by the electrostatic field between two spherical plates at potentials U_2^{defl} and U_3^{defl} and focussing lenses in front of and behind them, kept at potentials U_1^{defl} and U_4^{defl}, respectively.[45]

A subsequent lens at the potential[46] U_2^{foc} focuses the ion beam into the cesium cell. There, by interaction with cesium vapour, the ions are neutralized to metastable atoms. A strong magnetic field is produced by the current $I^{solenoid}$ in the water-cooled hollow conductor coils.[47] The cesium is evaporated by heating the supply vessel (I_1^{heat}). Furthermore, the wall surrounding the vapour in the interaction region is heated separately (I_2^{heat}). The temperatures T_1^{Cs} of the cesium-supply vessel and T_2^{Cs} of the wall are measured by Pt100 resistors and are kept constant by regulating the power supply units.

In the spin filter, atoms in the different nuclear hyperfine states are selected by superposition of a ramped longitudinal magnetic, a static transverse electric, and an rf field. The magnetic field is varied by a ramp generator that controls the power supply (see footnote 40) of the current in the solenoid coil. The coil is made from solid Cu wire in order to achieve the necessary field homogeneity. The cooling water is guided in a separate tube system, not depicted in Fig. 3. When the temperature T^{cav} of the cavity wall, measured with a Pt100 resistor, exceeds a preset limit, the power supply is switched off. The four quadrants of the cavity are kept at the static potentials U_1^{SF} to U_4^{SF} by four individual power-supply units.[48] The rf field in the cavity is fed by a combined oscillator and amplifier unit.[49] The rf power is monitored via the voltage signal from a diode sensor.[50]

In the quench chamber, the transmitted metastable atoms finally emit light in the strong electric field of the lens, kept (see footnote 40) at a potential U^Q. The light intensity is measured with a photomultiplier[51] as a function of the ramped magnetic field in the spinfilter. When the heating in the Cs cell is switched off, the ion current I^{ion} behind the quench chamber can be measured with a Faraday cup.

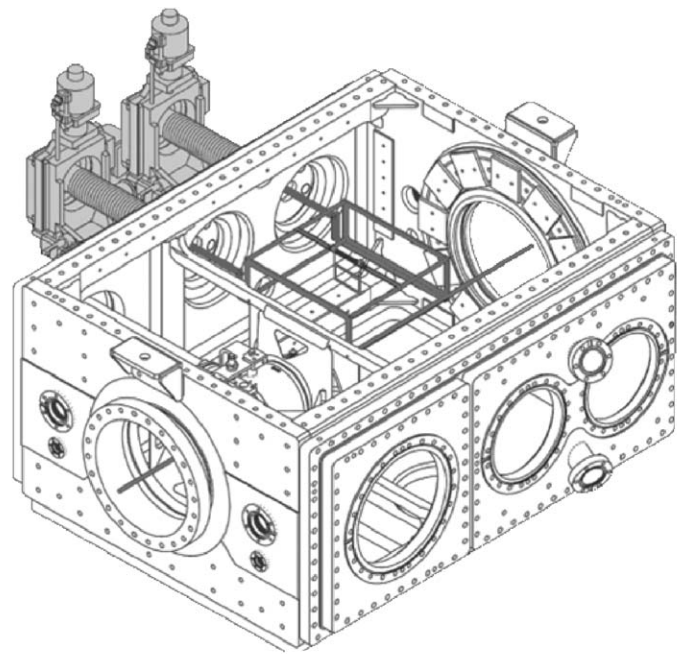

Fig. 4. 3D CAD drawing of the ANKE-target chamber with the two manipulators carrying the frame with a diaphragm used for beam diagnostics. The COSY beam enters the chamber from the left.

The deflector chamber and the quench chamber are pumped by turbomolecular pumps[52] and a diaphragm pump.[53] The pumping speed at the deflector chamber is increased by an additional cryogenic pump (see footnote 28), supplied by a He compressor (see footnote 12). In both chambers, the pressures are measured with a combined Pirani/Bayard-Alpert (hotcathode) gauge (see footnote 32).

2.3. Components of the target-cell positioning system

A stepper-motor driven support system has been built which allows, without breaking the vacuum, the positioning of a set of different diaphragms and prototype-storage cells onto the COSY-beam axis within the ANKE target chamber. Intensity, lifetime and profile of the COSY beam are studied to optimize the operation parameters and to identify the optimum dimensions of the storage-cells. Two identical X–Y–Z manipulators[54] carry a light frame, in

[42]LCU 1200-20, Heinzinger electronic GmbH, D-83026 Rosenheim, Germany (now division of Knürr AG (see footnote 36)).

[43]Power supply SM 15-200 D (0–15 V/0–200 A), Delta Elektronika BV, NL-4300 AA Zierikzee, The Netherlands (distributor: Schulz-Electronic GmbH, D-76534 Baden-Baden, Germany).

[44]Symmetric positive and negative voltages supplied by NCE 1200-25 (0–1200 V/0–25 mA), Knürr AG (see footnote 36).

[45]All voltages from LCU 1200-10 supply units, Heinzinger electronic GmbH (see footnote 42).

[46]Power supply NCE 1200-25 (0–1200 V/0–25 mA), Knürr AG (see footnote 36).

[47]Power supply NTN 700-35 (0–35 V/0–20 A), F.u.G. Elektronik GmbH (see footnote 35).

[48]NCE 3000-10 (0–3000 V/0–10 mA), Knürr AG (see footnote 36).

[49]RFS 1600-05, R.F.P.A. SA (see footnote 16).

[50]Type 04018, EME Karl Müller, D-82969 Hohenschäftlarn, Germany.

[51]High voltage supply by PNC 6000-10 ump (± 6000 V,10 mA), Heinzinger electronic GmbH (see footnote 42).

[52]TMH 261, Pfeiffer Vacuum GmbH (see footnote 25).

[53]MVP 055-3, Pfeiffer Vacuum GmbH (see footnote 25).

[54]HPT Translator, Z-module MRXZ1515 with stepper motor MRXMOTZ, X/Y module MRXXY12 with stepper motor MRXMOTY, Vacuum Generators (see footnote 21).

which the diaphragms and prototype tubes are suspended (Fig. 4). The stepper motors[55] on both manipulators allow independent remote-controlled movements in the horizontal (x_C) and vertical (y_C) direction, perpendicular to the COSY-beam direction.[56] Due to the negligible change of the beam profile along the tube, no movement in the beam direction (z_C) is needed. The two manipulators allow parallel shifts of the frame by 150 mm in x_C and by ±12.5 mm in y_C direction. They also allow one to tilt the frame in any direction. Upper limits in the tilting angles of ±2° have to be assured, which are set by the mechanical connection between the frame and the flanges on the manipulators. The positions of the two travelling flanges of the manipulators, carrying the frame, are monitored by multi-turn angle encoders.[57]

With use of two manipulators, two CF160 flanges at the target chamber are occupied. In order to allow for other installations, a new setup is under preparation, which will make use of a single manipulator, allowing increased 300 mm horizontal (x_c) and ±25 mm vertical (y_c) movement, and a rotation of the frame within the horizontal x_c–z_c plane only.[58] This restriction of freedom takes into account the fact that the vertical inclination of the COSY beam is small and, therefore, the storage-cell tubes can be positioned onto the beam axis without any tilt in the y_c–z_c plane.

3. Control-system technologies

3.1. Basic design issues

The exclusive use of industrial control technology is important for the PIT control system to ensure reliable operation under any circumstance. The robust industrial PLC technology is ideally suited for this purpose. The control of the system constitutes a typical slow control problem with moderate requirements of reaction time and data throughput. Since the control system up to now employs about 800 process signals, it could be implemented on a single PC. It should, however, be possible to extend the control system to a distributed configuration with more than a single PC. An additional boundary condition was the restricted manpower. Therefore, powerful development tools were desired. Since the technical specifications of the PIT have been continuously evolving and subsystems had to be tested individually, a high degree of flexibility was required from the development tools.

The basic decisions in the design of the control system were related to the choice of the front-end PLC and input/output systems, the communication technology, and the toolkit for the SCADA system. These three basic components determine the flexibility and extendibility of the system, as well as efficiency of the software development and the total cost of the system. In the following subsections these topics are discussed in detail.

3.2. PROFIBUS

As an international standard, the PROFIBUS (see footnote 5) has become the most widely accepted modern fieldbus technology in Europe [12]. A major reason for its success is the technological and functional scalability based on a common core. Nowadays, a wide range of PLCs, as well as low-cost process input/output modules are available from a variety of manufacturers, which greatly simplifies the interfacing. Most of the installed PROFIBUS equipment follows the DP profile, which has been designed for the optimized connection of simple, low cost input/output modules in a real-time environment. The DP system maps them transparently to a dual-ported RAM in the host system.

3.3. The S7 PLCs

The S7 series constitutes the actual PLC line of Siemens, the dominating manufacturer of industrial automation equipment on the European market. In addition, the S7 series is equipped with powerful development and diagnostic tools. A large variety of modules is available, providing special modules for complex functions, e.g. stepper-motor or PID controllers. PROFIBUS is the well-supported tool for external connectivity. PLC periphery can be transparently extended by decentral periphery units ET200, i.e. distributed inputs and outputs. The S7 series offers a wide spectrum of CPUs, enabling a high degree of scalability with regard to performance and functionality. In all PLCs, the CPU 315-2 DP (see footnote 4) is used.

3.4. WinCC

The main functions of the process-control software on the supervisory computer at the PIT are

- monitoring, i.e. visualization of the process status and history,
- allowing operator control, like setting of parameters, switching subsystems on and off, acknowledgement of alarms,
- archiving of process variables and alarms, and
- communication with the process periphery and supervisory computers, e.g. the ANKE data-acquisition systemcv.

A main requirement was the availability of powerful development tools for the SCADA software in order to achieve high development efficiency and to facilitate

[55]Driven by power supplies CCD 93-70 MINI-H-5, Phytron-Elektronik GmbH, D-82194 Gröbenzell, Germany.

[56]The correspondence between the coordinate systems, used by Vacuum Generators (vg) and at COSY (c), is $x_{vg} \equiv z_c$, $y_{vg} \equiv y_c$, and $z_{vg} \equiv x_c$.

[57]Model ROQ 425, Dr. Johannes Heidenhain GmbH, D-83301 Traunreut, Germany.

[58]Transax Translator, Z-module MTX3070 with stepper motor MTRSMK, X/Y module MT208A6S with stepper motor MT08Y, and rotary drive module MR1T with stepper motor ZRDPMK, Vacuum Generators (see footnote 21).

expansions and modifications. The existence of interfaces and of proprietary protocols providing access to Siemens S7 PLCs, its long-term availability on the market and the natural integration with the PROFIBUS DP led us to choose the Siemens product WinCC. WinCC is a SCADA toolkit for the PC platform, available for the Windows 2000 and Windows XP operating systems. The main components of the employed WinCC package are

- a graphical editor—process pictures can be comfortably drawn and the attributes of graphical objects can be connected to process variables in a transparent way,
- an alarm system,
- a database—WinCC integrates the database Microsoft **SQL**[59] server for the storage of process values and alarms,
- a variety of channel **DLL**s (**D**ynamic **L**ink **L**ibrary) supporting industrial networks and PLC types, and
- an integrated script interpreter, based on **ANSI** C (**A**merican **N**ational **S**tandards **I**nstitute), allowing modification of dynamic actions during runtime, thus increasing development productivity. The use of ANSI C allows a simple port of code between script modules and conventionally implemented modules. Scripts can directly call functions and access variables in Windows DLLs.

WinCC is an open system supporting standard Microsoft technologies like

- **OLE** (**O**bject **L**inking and **E**mbedding): a mechanism for exchanging data between programs, e.g. for the integration of a Microsoft Excel worksheet in a WinCC process screen,
- **DDE** (**D**ynamic **D**ata **E**xchange): an interprocess-communication mechanism,
- **ActiveX**: WinCC offers ActiveX container functionality for easy integration of market-available ActiveX controls,
- **ODBC** (**O**pen **D**ata **B**ase **C**onnectivity): it provides an open interface to the process database for external applications, and
- the **OPC** (**O**LE for **P**rocess **C**ontrol): a de-facto standard protocol for the access to devices aiming at the interoperability of automation systems.

The WinCC system is scalable by supporting multi-client/multi-server configurations.

The development focused on graphical programming using the WinCC integrated graphical editor. Additional actions on script level were requested to handle more complex tasks and operations like format conversions or scaling of process data. Many control algorithms were first tested in the form of script modules and later implemented in the PLC or even on the gateway. This approach could only be used for very slow tasks, because the process variable updates as well as the maximum calling frequency of script actions are limited by WinCC to 4 Hz. Faster operations could be implemented by DDE servers using the WinCC DDE channel.

[59]A Microsoft product using the **S**tructured **Q**uery **L**anguage.

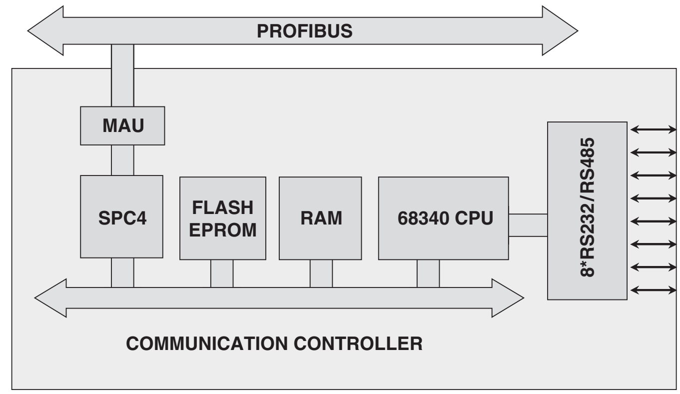

Fig. 5. Block diagram of the serial gateway developed at FZJ. MAU denotes a Medium-Access Unit containing optocoupler and galvanic decoupling. (Further explanations can be found in the text.)

3.5. Serial gateway

As a spin-off from an industrial project, a PROFIBUS DP slave for devices with serial interface has been developed in Jülich that is equipped with 8 serial channels supporting RS232 and RS485 (Fig. 5). The controller core is implemented as an intelligent subsystem with a central address/data/communication-control bus connecting the CPU MC68340FE16, the 512 KByte Flash EPROM, the 256 KByte static RAM, and the protocol chip SPC4. An embedded application software on the MC68340 implements those parts of the serial protocols for serial devices (e.g. control units for Pfeiffer vacuum pumps, MKS control units for vacuum gauges) that are required by the PIT application. The system serves as a gateway between these serial protocols and PROFIBUS DP. Via this gateway, the process-control computer can directly access pressures, status, set points or rotational speeds in the DP image, transferring protocol handling and polling operations to the gateway.

4. Logical structure of the control system

One of the guiding principles for the design of the control system was the implementation of a modular structure based on the schemes shown in Figs. 2 and 3.

4.1. Polarized atomic beam source

Four subsystems can be distinguished in the general scheme of Fig. 2.

(1) Vacuum system
The vacuum system is responsible for the automatic evacuation and venting procedures and for the

automatic regeneration procedure of the cryogenic pumps, which can be started by the operator via **GUI** (**G**raphical **U**ser **I**nterface). In addition, an emergency shutdown can be initiated by the interlock system. All relevant parameters are continuously monitored, displayed and saved in the online database. These include the pressures of all vacuum gauges as well as the status of all heaters, valves, compressors, and pumps. The temperatures of the cryogenic pumps and the rotational speeds of the turbomolecular pumps are monitored as well. During the evacuation procedure, illustrated in Fig. 6, the backing diaphragm pumps, the turbomolecular pumps (TMH 260 C and TPH 2200 C), and the cryogenic pumps are sequentially started on the base of the pressures measured in the different chambers. The automatic procedure includes also the control of the bypass valves between the ABS chambers and the activation/deactivation of the vacuum gauges according to their measuring ranges.

(2) Dissociator and nozzle cooling
Via the GUI, the operator can set the flow of molecular hydrogen or deuterium and select a small admixture of oxygen to be injected into the dissociator, as well as the parameters of the rf generator for the plasma discharge. Furthermore, the control system is responsible for the temperature stabilization of the beam-forming nozzle via a PID loop. The operational stability of dissociator and nozzle is monitored via the pressures in the dissociator and the ABS-vacuum chambers and by the intensity of the polarized atomic beam, i.e. by the pressure in the ANKE-target chamber, hosting the storage cell, and the count rate in the detectors. The flow Q of the coolant and its inlet (T_{in}) and outlet (T_{out}) temperatures (Fig. 2) allow one to monitor the dissociator operation.

(3) rf-transition units
Remote operation of the three rf-transition units has been implemented. The operator can monitor and select the frequency and the output voltage of the rf generator for each transition and switch on/off the corresponding amplifier via the GUI. Furthermore, it is possible to set the currents $I_{homogen}$ and $I_{gradient}$ of the five power-supply units for the coils producing the magnetic homogeneous and gradient fields (Fig. 2) and monitor currents and voltages. For the magnets a degaussing procedure has been implemented.

(4) Interlock system
The interlock system is responsible for the detection of faults and the implementation of actions required to prevent damage of the system. Continuous monitoring of all the parameters of the vacuum system is a major task of the interlock system and most fault conditions require an emergency or regular shutdown of the vacuum system. Besides the parameters of the vacuum system, the supply of coolants and compressed air are monitored as well as the status of the leak detectors. Furthermore, venting of the ABS and LSP vessels has

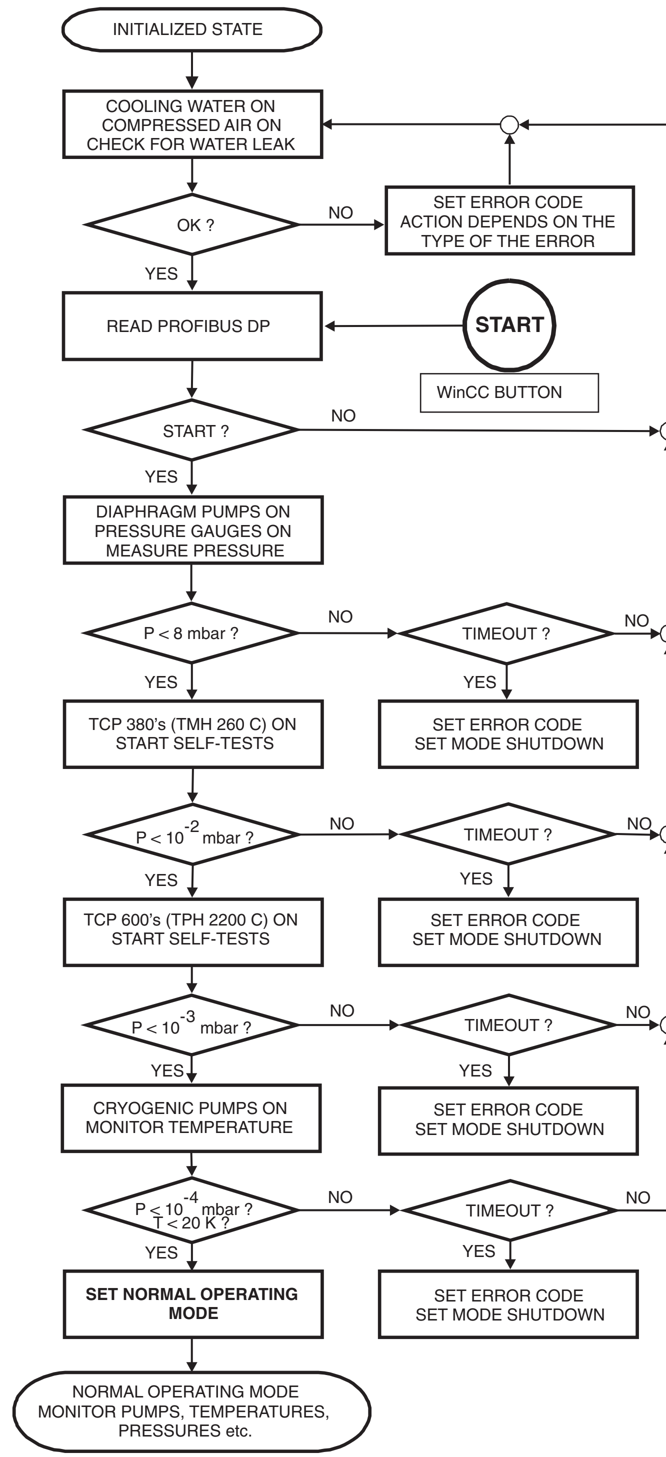

Fig. 6. Simplified flow diagram of the automatic evacuation procedure for the ABS.

to be inhibited until the nozzle and the cryogenic pumps have warmed up. For unforeseen electrical power outages, an **UPS** (**U**ninterruptible **P**ower **S**upply) unit[60] has been installed in order to ensure a controlled shut-down to a well-defined final state of the whole

[60]Smart UPS 1400 (1400 VA), American Power Conversion (APC), distributor Pro-Data Service GmbH, D-41516 Grevenbroich, Germany.

setup. The UPS is used to bridge short-term power failures, not necessitating an emergency shut-down.

4.2. Lamb-shift polarimeter

The scheme of Fig. 3 shows those components that have to be controlled. They can be subdivided into vacuum system, voltage-supplies, and current-supplies.

(1) Vacuum system
The pumping down by the two stages of turbomolecular pumps and the cryogenic pump is done in an automatic procedure similar to the one described in the flow diagram of Fig. 6. The pressures in the deflector and the quench chamber are used in the interlock system. As in the ABS, the pressure measured by the piezoelectric gauge is used to set an upper limit to the venting pressure.

(2) Voltage supplies
The potentials of the lenses and electrodes are optimized manually to achieve the maximum peak heights in the spectrum from the photomultiplier at the quench cell. Thereafter, the potentials are monitored and any deviation outside the preset limits leads to a warning signal, calling for operator intervention. It is foreseen to develop and to implement automatized optimization and stabilization procedures. The power of the rf field in the cavity of the spin filter is monitored by the crystal detector indicated in Fig. 3. Shifts of the cavity temperature T^{cav}, monitored by a Pt100 resistor, result in changes of the cavity-resonance properties. With the rf frequency kept constant, the power of the rf field is stabilized by regulating the rf-generator power according to the amplitude changes of the crystal-detector signal.

(3) Current supplies
The currents in the three solenoid coils are set via the GUI and their stability is monitored. In the Cs cell, the temperatures T_1^{Cs} of the liquid Cs and T_2^{Cs} of the cell wall around the Cs vapour are stabilized at 160 and 60 °C, respectively, within ±1 °C by varying the heating currents I_1^{heat} and I_2^{heat}. To activate the material of the nonevaporable getter pump after venting or long operation, the modules have to be warmed up to 400 °C for about 30 min. The temperature is monitored by three sensors mounted on the getter modules themselves.

(4) Interlock system
The interlock system prevents getter-pump activation, heating of the electron-emitting filament, and heating of Cs as long as the pressure in the LSP chambers exceeds 10^{-5} mbar. Furthermore, the currents in the solenoid coils can only be switched on, if the sensors confirm the flow of the cooling water. The current in a coil is switched off, if a temperature sensor, installed on the coil, indicates a value exceeding a preset upper limit. A piezoelectric gauge, installed on the deflector chamber, limits the pressure during venting to ~1020 mbar by controlling the venting valve.

4.3. Target-cell positioning

The only issue to be faced in the design of the control system for the target chamber is the movement of the four axes of the support system for the target cell. For all the axes, status and position are displayed and movement can be started by the operator via the GUI. The control system continuously monitors the position difference along the x-axes and the y-axes in both X–Y–Z manipulators and stops the movement, if the limits of the tilt angles are exceeded. In a first version, absolute positioning was done by counting the steps of the stepper motors from reference-point switches. In order to avoid positioning errors caused by losses in the counting of motor steps, angular encoders are now used. Their reference positions are still determined with the use of the reference-point switches. Referencing is started by the operator via the GUI. An envisaged new setup with a single manipulator will require only minor modifications.

5. Physical structure of the control system

5.1. Overview

The physical architecture of the control system follows a horizontal and vertical structure as displayed in Fig. 7. Vertically, it is organized into layers. On the top layer, there is one central process-control computer, a **PICMG** (**P**eripheral **C**omponent **I**nterconnect **I**ndustrial **C**omputer **M**anufacturers **G**roup) passive backplane PC with a Pentium M CPU.[61] Microsoft Windows 2000 is used as operating system and PROFIBUS connectivity is achieved with the PROFIBUS-controller board CP5613 (see footnote 4). Both the process-data base and the operator interface reside on this machine. In a client/server configuration, which in principle is possible with WinCC, an additional layer of computers above the central control computer would be introduced, where the operator interface would be running. For the connection to the ANKE data acquisition (DAQ), a simple protocol based on **XDR** (**EX**ternal **D**ata **R**epresentation) and **UDP** (**U**ser **D**atagram **P**rotocol) has been implemented, that allows transparent access to internal WinCC tags via Ethernet. Thus, the ANKE DAQ can download setups to the ABS and continuously read back its status for inclusion in the data stream. The same protocol is used by a physics workstation for experimental tests of the

[61] PCI-ISA Passive Backplane Standard with AXIOMTEK SBC81871V2G CPU board, distributor AXIOMTEK Deutschland GmbH, D-40764 Langenfeld, Germany.

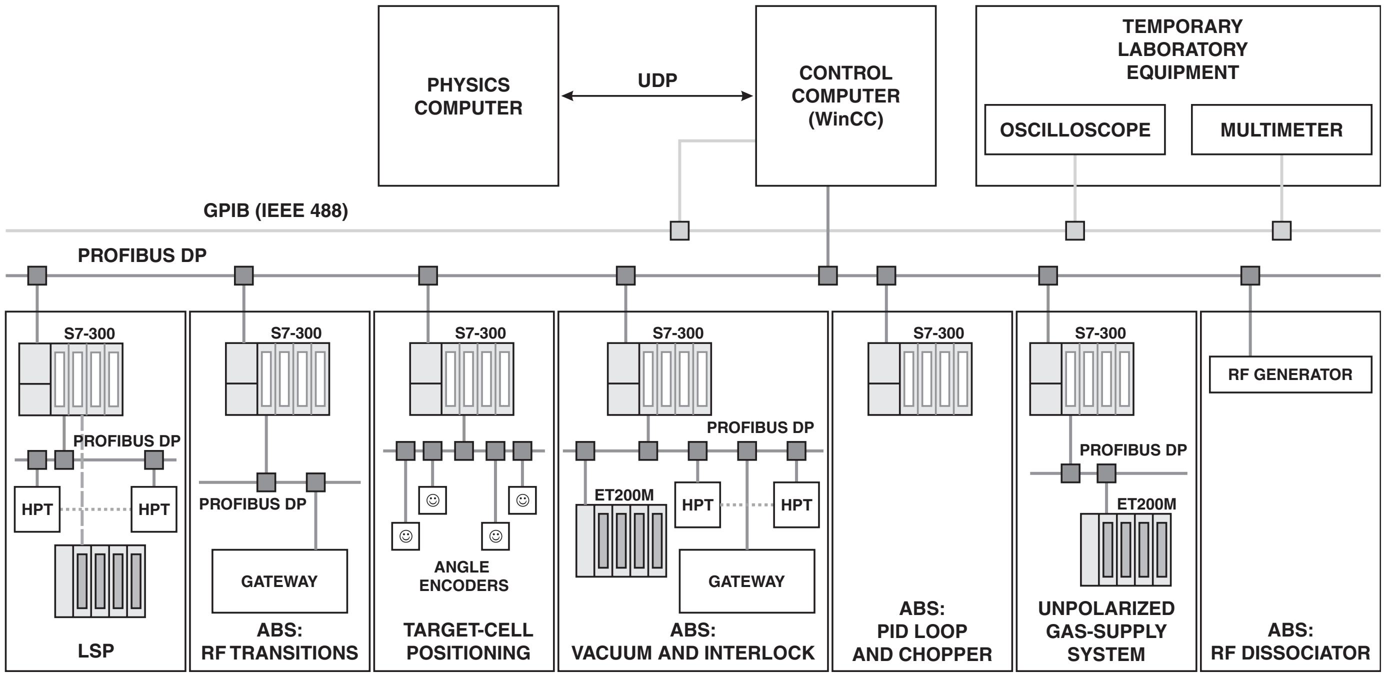

Fig. 7. Structure of the control system for the polarized internal target (PIT) of ANKE–COSY. The unpolarized gas-supply system is a temporary diagnostic tool, described elsewhere [13].

ABS itself. The second layer consists of intelligent devices, which are all connected via PROFIBUS DP. Diagnostic tools can be connected via a **GPIB** (**G**eneral **P**urpose **I**nterface **B**us).[62] Devices without a direct PROFIBUS connectivity but with a serial RS485 or RS232 interface are connected via the serial gateway. Most process equipment is connected to the six S7-300 PLCs controlling the individual subsystems. Part of the equipment is not directly attached to the PLCs. Instead, it is connected via secondary PROFIBUS DP segments and ET200M decentral periphery systems residing on a third layer. Thereby, the cabling effort is reduced considerably.

All PLCs are equipped with the same CPU, the CPU315-2 DP (see footnote 4) with integrated PROFIBUS and **MPI** (**M**ulti **P**oint **I**nterface[63]) connection. The modules, used for the different inputs and outputs in all PLCs and in all ET200M devices, are the following:

- for all digital inputs and outputs the module SM321 (see footnote 4) and SM322 (see footnote 4), respectively, which are both 32-channel modules with signal levels of 24 V,
- for all analog inputs the module SM331 (see footnote 4), an eight-channel module with a variety of configurable voltage-, current- or resistance-measurement modes, and
- for all analog outputs the module SM332 (see footnote 4), a four-channel module with a variety of configurable voltage- or current-output modes.

[62]Defined by IEEE 488.1.

[63]A serial bus defined by Siemens.

Signal-distribution and signal-adaptor units are used for the connection to the front-end devices. They contain relays for those contacts, which have to be potential-free, and relays needed for conversion of signals to the TTL level or for the switching of power in the 400 and 230 V lines. These units allow simple mechanical connection of the cables between the PLCs and the controlled devices. When a connection to a secondary PROFIBUS segment is required, the internal PROFIBUS interface of the CPU315-2 DP is employed. In these cases, the PLC is equipped with the additional PROFIBUS controller CP342-5 (see footnote 4) for the connection to the primary PROFIBUS segment.

Horizontally, the system architecture reflects the logical structure of the control system, since each PLC is responsible for a logical subsystem. Thus, the complexity of the PLC software could be reduced and the overall modularity could be increased. Each PLC can operate autonomously without communication with supervisory computers or other PLCs. An exception is found in the PLC responsible for the vacuum system. It implements all major safety-related interlocks, because these are closely integrated into the vacuum system operation. It is also responsible for the overall system start and shutdown, and it handles the required communication with other PLCs.

5.2. *Polarized atomic beam source*

As it can be seen from Fig. 7, the PLC for the ABS subsystem **VACUUM AND INTERLOCK** is connected to a secondary PROFIBUS segment to access an ET200M unit, the pressure gauges with PROFIBUS DP gateway (see footnote 32) (labeled HPT), and the serial gateway. The latter provides the connection to the other types of pressure gauges (see footnotes 10, 31), to the gas-flow controllers (see footnote 6), and to the controllers of the turbomolecular pumps. The ET200M is located in a remote rack containing the sensors which monitor the cooling water flow and the compressed air. The vacuum and interlock system includes three digital input and three digital output modules allowing 96 input and 96 output channels, four analog input modules allowing 32 input channels, and 30 PROFIBUS-gateway connections. The controlled devices include (Fig. 2):

- seven turbomolecular pumps, switched to different operation states and monitored concerning status and rotation frequency,
- three diaphragm pumps, switched on and off,
- four cryogenic devices, switched on and off and monitored,
- three heater units at the cryogenic pumps, controlled during the heating cycles for regeneration,
- four Si-diode control units,
- seven electro-pneumatic valves, opened, closed, and monitored concerning the status,
- two electro-magnetic valves, opened and closed,
- two gas-flow controllers and five pressure gauges in the modular MKS system, monitored by the serial gateway,
- two pressure gauges with PROFIBUS gateways,
- one piezoelectric pressure gauge,
- one water-leak detection system,
- one flow meter and two temperature sensors monitoring the dissociator coolant, and
- a variety of sensors for the supply of cooling water and compressed air.

In the ABS subsystem **RF TRANSITIONS**, the PLC is connected to a secondary PROFIBUS segment for access to the serial gateway, which interfaces the function generators for the MFT, WFT, and SFT units. The PLC includes 11 channels of one digital output module, 16 channels of two analog input modules, eight channels of two analog output modules, and three channels via the PROFIBUS gateway. The controlled devices are (Fig. 2):

- three rf generators, frequencies and powers set and monitored via the PROFIBUS gateway,
- three rf amplifiers, switched on and off, frequencies and powers monitored via the PROFIBUS gateway, and
- five power-supply units for the magnetic fields in the transition units, with currents set and voltages and currents monitored.

In the ABS subsystem **PID LOOP AND CHOPPER**, the S7-300 PLC serves to set and stabilize the temperature of the dissociator nozzle. The PLC is equipped with a FM355C (see footnote 4) function generator, a four-channel autonomous PID controller containing all necessary analog inputs and outputs for the implementation of four continuous or two-point control loops. One loop is responsible for the temperature of the nozzle. A FM353 (see footnote 4) stepper-motor controller regulates the rotation of the beam chopper. The amplifier of the photodiode signal is connected to the reference-point input of the FM353.

In the ABS subsystem **RF DISSOCIATOR**, the rf generator that feeds the discharge in the dissociator tube is switched on and off by two digital output signals. A PROFIBUS gateway channel is used to set the rf power and the adapter network. Furthermore, stable operation of the dissociator is controlled by monitoring the coolant flow, its inlet and outlet temperatures, and the rf power reflected from the adapter network.

5.3. Lamb-shift polarimeter

In the subsystem **LSP**, the PLC is organized into three rows, connected by IM360 (see footnote 4) and IM361 (see footnote 4) repeaters in order to mechanically fit into a standard 19 in. rack. The PLC contains two digital input and two digital output modules, allowing 64 inputs and 64 outputs, 12 analog input modules with 96 channels in total, and seven analog output modules with 28 channels in total. The controlled devices comprise

- three turbomolecular pumps, one diaphragm pump, and one cryogenic pump, all controlled and monitored as described in Section 5.2,
- one nonevaporable getter pump during the regeneration procedure,
- two pressure gauges with PROFIBUS gateways,
- two cooling-water flow meters,
- 23 current/voltage supply units,
- one magnetic-field ramp generator,
- one rf generator, operated at a fixed frequency of 1.60975 GHz and power-controlled by the signal from the crystal-diode to stabilize the rf power in the spin-filter cavity,
- one rf amplifier, switched on and off, and
- one crystal-diode, the signal of which is used to regulate the rf-generator power.

5.4. Target-cell positioning

In this subsystem, the PLC is connected to a secondary PROFIBUS segment to access the four angle encoders. The interfacing to the four stepper motors uses FM353 (see footnote 4) function modules. These are intelligent controllers which autonomously take into account limiting and optional reference-point switches. However, as they cannot interface the angle encoders directly, the detection of lost steps has to be carried out by the PLC CPU itself.

5.5. Unpolarized gas-supply system

This subsystem, indicated in Fig. 7, is used to provide a calibrated flow of unpolarized gas. It is employed, e.g., to calibrate the compression-tube setup [13] for measurements of the ABS intensity. This subsystem can be included into the PIT-control system. Until now, however, it was used as a stand-alone device.

6. Tools for parameter studies

For the investigations and optimization of the ABS-beam properties, a special software has been developed using Borland Delphi,[64] supplementing the subsystem **Temporary Laboratory Equipment**, indicated in Fig. 7. It runs on a separate "physics PC" and provides automatic scanning of selected ABS parameters like nozzle temperature and dissociator power, while other specified process variables are read and archived for each point. Different sequences of such measurements are also implemented, allowing us to combine scans of different parameters into one automatic procedure. The software communicates with WinCC using UDP based upon the XDR standard. It also allows the use of diagnostic tools like an oscilloscope, connected via the GPIB, or the multi-wire monitor for atomic beam-profile measurements [14], controlled by a special self-made board. This software allows one to carry out long-term measurements without operator control.

7. Conclusions and outlook

The experience obtained during development and use of the control system justifies our initial design decisions. The system proved to be flexible and extensible. In particular, the selection of PROFIBUS DP made the integration of new components very simple. The main increase of productivity was caused by WinCC, which allowed easy extensions and modifications of process pictures. Transparent access to the PLCs via PROFIBUS DP, the predefined alarm system and the integrated database were key benefits. The only difficulties occurred when the change from Windows NT to Windows 2000 necessitated the upgrade of WinCC from version 4.2 to version 6.0. The use of the Project Migrator,[65] required for the conversion of WinCC applications, enforced deletion and new implementation of the alarm subsystem.

The development phase of the ABS-control system included a few hundred startup and enforced shutdown procedures, mainly required for the systematic tests of the interlock system. The longest continuous ABS operation covered a period of about four months. Under all conditions, the front-end PLCs and the controlling PC with WinCC proved to be reliable. Out of about 100 modules in total, two failed and had to be replaced. The slow control and interlock system of the ABS and the positioning device are fully functional. The latter has been successfully used during two beam times for remote adjustment of diaphragms and storage-cell prototypes onto the COSY-beam axis and to move them around the central beam position for systematic studies of the COSY-beam properties. Some work is still required to finalize the LSP-control system.

The WinCC-inherent limitation of process-variable updates to 4 Hz restricts its functionality to operator control (setting and visualization of process variables) and archiving. At our moderate number of less than 1000 process variables, no overload situations occurred with regard to communication or database access. The reaction time of the GUI was always below 0.5 s.

The knowledge and experience, gathered with the present control system, has been successfully applied in the development of new control systems elsewhere, i.e. for part of the instruments installed at the FRM-II research reactor in Garching near München [15] and at the vacuum system of the TOF experiment at COSY-Jülich [16].

The ABS and the positioning device, carrying a storage cell and a diaphragm, have been installed at the ANKE-target chamber for commissioning studies, to be performed towards the end of 2005. For the future experiments, the present operation mode of the ABS rf-transition units has to be modified to allow one to alternate automatically between different nuclear polarization states of the target. A bit pattern, representing the actual ABS-operation state, has to be included into the ANKE data stream. During each measuring interval, additional ABS operation parameters like pressures, temperatures, rf powers have to be added to the stored event data. Further plans concern the inclusion of a webserver as well as a mechanism to access the process database from Linux based systems.

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