NEW K130 CYCLOTRON AT JYVÄSKYLÄ

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ABSTRACT

Installation of the K130 cyclotron and its ECR ion source was completed during 1990–91. The first plasma in the ECR was produced in May 1991. The first experiment using the ECR beam was carried out in September 1991 when 50 keV $^{40}Ar^{5+}$ was used to bombard a Cu sample for a material-physics experiment. The beam was injected for the first time into the cyclotron in December 1991. The first beam was extracted on January 28, 1992. The beam was 6.0 MeV/u $^{4}He^{1+}$. During the spring 1992 also a heavy-ion beam of $^{40}Ar^{10+}$ was successfully accelerated. The construction of the experimental hall was completed in June 1992.

1. BACKGROUND

The earlier history of the Jyväskylä cyclotron project can be found in the proceedings of the Berlin-89 cyclotron conference.[1)]

The K130 cyclotron project was started in September 1986 with the appropriation of about 7 million USD in the Finnish state budget for the years 1987–91. The funding included the K130 cyclotron, the ECR ion source and the injection line. Funding for the building was secured only afterward, which resulted in unnecessary delay. No beam-transport system nor any experimental equipment were included in the initial funding decision. They will be funded through the annual budgets of the University in 1992–96.

In order to keep costs and own man power to a minimum, commercial manufacturers were used as much as possible. The main parts of the K130 cyclotron were manufactured and delivered by the Swedish company Scanditronix AB. Scanditronix also delivered the vacuum chamber, extraction and RF systems and most of the power supplies. The Department of Physics was responsible for the rest of the facility, including the control system, installation and testing. The ECR ion source and injection line were also built locally.

Figure 1 shows a general view of the cyclotron in its bunker, the injection line and the ECR ion source. The main parameters of the K130 cyclotron are given in Table 1.

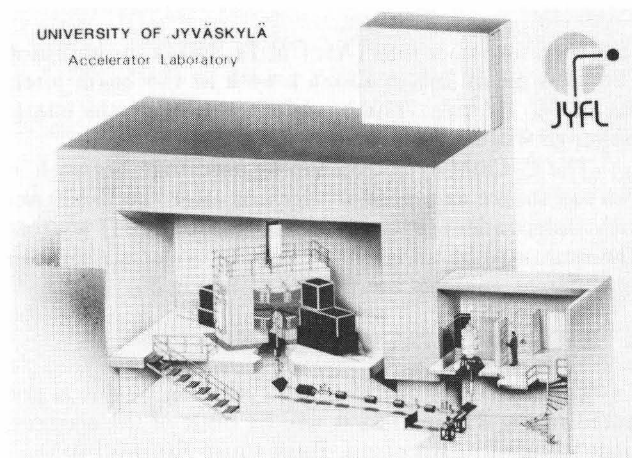

Fig. 1. Three-dimensional sketch of the K130 cyclotron with the ECR ion source and injection line.

2. MAGNET AND RF

The K130 cyclotron has three 58° spiral sectors, 15 circular correction coils and four sets of harmonic coils. The bending limit of the magnet is 130 MeV and the focusing limit is about 90 MeV. The magnet was computer designed by the Department of Physics and built without a model magnet.[2)]

The magnet was assembled by Scanditronix in Uppsala, Sweden, in January 1989. The pole configuration and shimming were confirmed during the spring 1989. The liners with the circular trim coils were installed in August–September 1989. The field mapping of the magnet was completed by Scanditronix in October 1989. Analysis of field-mapping data showed unacceptably large measuring errors. Therefore some fields were remapped in April 1990.

The RF system is of the resonator type and comprises two identical 78° dees, with associated dee stems and power amplifiers located on opposite sides of the cyclotron magnet. Both systems are driven by a common frequency synthesizer. The maximum dee voltage is 50 kV. The dees and dummy dees can be seen in Fig. 2.

Table 1. Parameters of the K130 Cyclotron

MAGNET			
pole diameter		2.4	m
pole gap, max.		0.33	m
min.		0.174	m
number of sectors		3	
spiral angle	max.	58	degr.
weight		308	tons
trimming coils, circular		15	
harmonic		4	sets
conductor		hollow Cu	
power, main coils		150	kW
trim coils		35	kW
field at 400 000 At, hill		2.1	T
valley		1.3	T
average		1.76	T
extraction radius		0.95	m
bending limit		130	MeV
focusing limit		90	MeV
ACCELERATION SYSTEM			
number of dees		2	
dee angle		78	degr.
beam aperture		3.0	cm
RF frequency		10–21	MHz
harmonic number		1, 2, 3	
max. dee voltage		50	kV
VACUUM			
2 cryo pumps	each	5000	l/s
operating pressure		10^{-7}	mbar
ION SOURCE + INJECTION			
external ECR			
axial + spiral inflector			
EXTRACTION			
dc electrostatic + EMC + 2 passive channels			
PARTICLE ENERGIES			
protons		6–90	MeV
other ions		$(0.2 - 1.0) \times 130\ q^2/A$	MeV

The RF power supplies, driven amplifiers and the control system are located in the power supply room. The entire RF system is remotely operated either from the panels in the power supply room or from the control system.

Each of the two RF cavities consists of a quarter-wavelength stem capacitively loaded by the dee at the high-voltage end. The stems enter the vacuum chamber via ceramic vacuum feedthroughs. Outside the chamber, each cavity consists of a horizontal coaxial stem with a movable grounding plate that provides coarse tuning within the 10–21 MHz range. Each system is fine tuned by a motor-driven capacitor facing the dee. The interdee phase can be set at any value (normally 180° or 0° degrees).

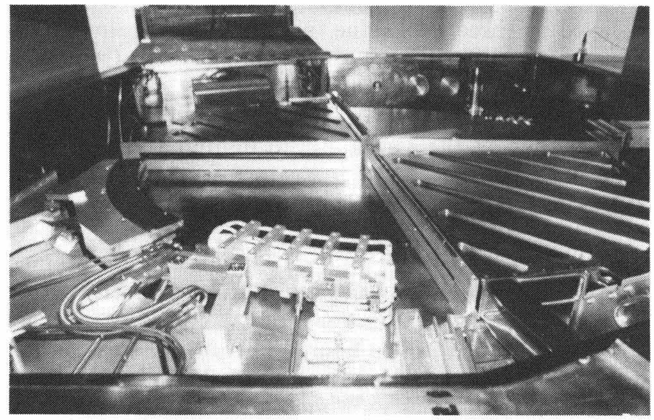

Fig. 2. Accelerator chamber of the K130 cyclotron. The extractor is in front. The phase probes and the central region were not installed in this photo.

The power amplifiers and the cavities for the two RF systems were completed and assembled in the autumn of 1989. The first RF tests were started in December 1989. The full power RF tests were successfully carried out in February–March 1990.

After the final factory acceptance tests in Sweden in April 1990, the cyclotron magnet was disassembled and packed for transportation. It arrived in Jyväskylä by rail in May 1990. The yoke with coils was reassembled in June 1990. The RF system arrived in Jyväskylä in June 1990.

The mounting of the cyclotron components and the cabling of its electronics were accomplished largely during 1990, but work on the smaller details continued through 1991.

3. VACUUM

The vacuum chamber is made of stainless steel and sealed against the poles with Viton O-rings. The accelerator chamber is pumped with two cryo pumps (5000 l/s each). The specified vacuum in the accelerator chamber was 10^{-5} Pa (10^{-7} mbar). The volume below the liners containing the pole, correction and harmonic coils is pumped by a small Roots pump. Outgassing from mild steel and epoxy is thereby excluded from the main vacuum. All feedthroughs for the correction coils are also kept outside the main vacuum. There are two types of safety valves between the high vacuum and the liner vacuum. Two of them work on gravity and six use thin foils with punctuation needles on both sides of the foil.

The vacuum chamber arrived from a subcontractor to the Scanditronix factory in August 1989. The first high-vacuum tests were carried out in November 1989.

A vacuum level of 10^{-4} Pa (10^{-6} mbar) was obtained with one cryo pump. However, the specified vacuum level could not be achieved until June 1990.

The vacuum chamber and liners were scheduled to be in Jyväskylä in the middle of June, but delivery was delayed by three weeks due to a fire on the train in Sweden. After difficulties with obtaining Viton O-rings of good quality, the vacuum chamber was pumped down for the first time in Jyväskylä in the middle of September 1990 using the same interim pumping system as in Uppsala.

The final vacuum tests were postponed until January 1991 when both cryo pumps were installed. A vacuum level of 1×10^{-5} Pa (1×10^{-7} mbar) was obtained after about 100 h of pumping. After a short venting with nitrogen, a vacuum level of 10^{-4} Pa (10^{-6} mbar) could be pumped in two hours. The ultimate vacuum of 3×10^{-6} Pa (3×10^{-8} mbar) was achieved after three months of continuous pumping later in 1991. This vacuum level is regarded as satisfactory. The last serious obstacle to fulfilling Scanditronix's specifications was thus removed.

The Scanditronix delivery was formally accepted on May 23, 1991 when the cyclotron group celebrated its first anniversary at the new laboratory.

4. EXTRACTION SYSTEM

An extraction system was manufactured by Scanditronix according to our calculations. The system consists of one electrostatic deflector (40°, 50 kV), one electromagnetic channel (EMC, 28°), two passive magnetic focusing channels, and one internal horizontal steering magnet for small directional corrections at the beam exit port. There is also a current probe between the deflector exit and the EMC entrance. The whole extraction system is placed on sliding arms so that it can be removed quickly from the cyclotron and transported to the shielded service area outside the cyclotron vault.

5. DIANOSTICS

In addition to the current probe in extraction, the K130 cyclotron uses one main radial current probe. This probe covers the whole acceleration range from the minimum radius of 14 cm. It can be brought completely outside the vacuum chamber and isolated with a valve. The main probe was constructed in our workshop.

In order to measure the phase history of particles during the acceleration, a phase-probe system was constructed in collaboration with Tampere Technical University. It consists of ten pairs of capacitive pickup plates mounted above and below the median plane of the cyclotron on radial supports. The pickup plates are multiplexed to a heterodyne system which makes use of a mixing technique across the 10 to 21 MHz band. With this technique, two fixed high-frequency signals are derived and fed to a phase-detecting circuit. Using compensation of RF disturbances, the system is able to determine the phase even at low beam currents. To achieve a good signal-to-noise ratio, the second harmonic is used. The phase-measuring system is controlled by the control system of the accelerator.

The phase-measuring system was completed in April 1992, and it has proved to be a very useful tool in cyclotron tuning.

6. ECR ION SOURCE

So far the only ion source for the K130 cyclotron is an ECR ion source. It was built in our workshop and it is similar to the RT-ECRIS at MSU[3] with some modifications and improvements. It is a vertical ion source with an iron yoke. One 6.4 GHz microwave transmitter with a power divider is used for two stages. The axial magnetic field is produced by nine circular coils using four power supplies. The radial magnetic field is created by strong NdFeB (Neo) permanent magnets.

A more detailed description of the Jyväskylä ECR ion source can be found in reference 3.

Figure 3 shows a photo of the ECR ion source surrounded by a high-voltage fence. Table 2 gives the essential parameters of the Jyväskylä ECR ion source.

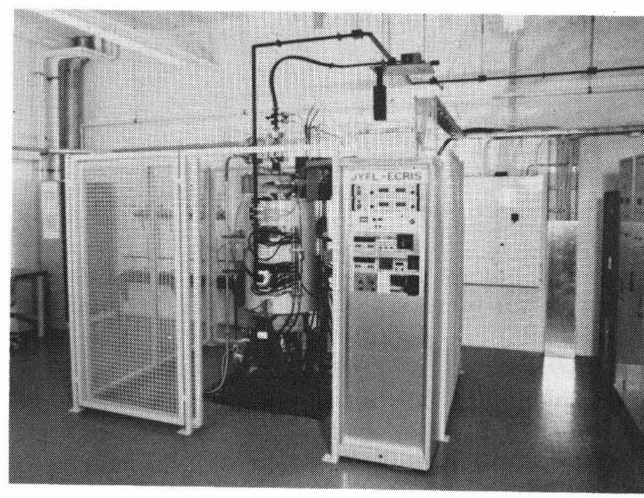

Fig. 3. Photo of the ECR ion source inside the HV protection fence.

Two ECR sources were made during 1987–91. The first one was for the Uppsala accelerator facility, where it has delivered heavy-ion beams to the Gustaf Werner cyclotron since November 1990.

The installation of the ECR ion source was completed in the winter 1990–91, but the testing could not be started before the water cooling system was ready in April 1991. The first plasma was produced in May 1991. The development of ion beams had to be halted for July and August 1991 when rock was being blasted behind the wall on the construction site of the experimental hall. The first beams (Ar^{5+} and Ar^{7+}) were delivered for an experiment in solid-state physics in mid-September 1991. Since September 1991 the ECR ion source has been used continuously, either to inject ion beams to the cyclotron or for solid-state physics. The remaining time has been used for developing new beams. As an example Fig. 4 shows a typical charge-state distribution of argon ions.

Table 2. Parameters of the ECR ion source

MAIN STAGE	
Lenght (adjustable)	40-50 cm
Diameter	14 cm
AXIAL MAGNETIC FIELD	
9 circular coils	
R=14.3 cm, ΔR=12.5 cm, Δz=4.0 cm	
3 double pancakes	
Conductor 0.64 × 0.64 cm^2	
Power consumption	35 kW
Maximum B on axis	0.38 T
Mirror ratio range	1.2 - 2.2
HEXAPOLE MAGNETIC FIELD	
Neo (B_r=1.15 T)	
Inner diameter	15.2 cm
Pole width	5.1 cm
Pole hight	3.8 cm
Pole length	76.5 cm
Max. field in plasma chamber	
Hexapole bar center	0.34 T
Hexapole gap center	0.27 T
MICROWAVE	
Frequency	6.4 GHz
Power, max.	3.3 kW
HIGH VOLTAGE	
Main	30 kV/10 mA
Extraction	-15 kV/20 mA
VACUUM SYSTEM	
2 turbo molecular pumps	
Injection chamber	330 l/s
Extraction chamber	500 l/s
Basic vacuum level	10^{-8} mbar

7. INJECTION LINE

The first focusing element in the injection line after the ECR source is a 40 cm long solenoid. It forms a waist at the object point of the double-focusing 90° analyzing magnet; its analyzing power is about 1/100 in mass with slits 1.0 cm wide. The analyzing magnet can be rotated around its vertical axis in order to send the beam either to the cyclotron or to solid-state experiments.

The horizontal transfer line consists of four evenly spaced 40 cm solenoids and a matching unit of four quadrupoles. A second 90° dipole bends the beam upward to the cyclotron axis, through which the beam is focused by two solenoids. The last yokeless solenoid is inside the cyclotron pole piece. Four small xy magnets are placed along the injection line. All magnets for the injection line were in place before the end of 1990.

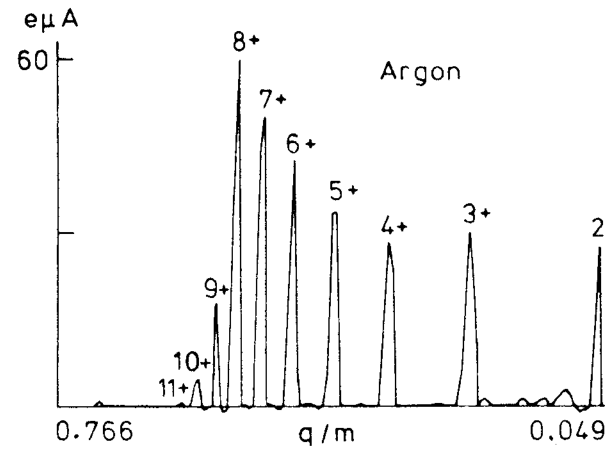

Fig. 4. Charge-state distribution of argon extracted at 10 kV. Microwave input power: 1st stage 16 W, 2nd stage 62 W.

Diagnostic equipment consisting of slits, Faraday cups and TV monitors was designed in our laboratory and produced partly by local subcontractors, partly in our workshop.

TV pictures are digitized using the same frame-grabber technique as at MSU.[5)] It gives a two-dimensional current-density picture instead of the more limited x and y projections. When ordinary phosphors, e.g. Al_2O_3:Cr, are used in low-energy heavy-ion beams, they get rapidly damaged; in typical cases they last only a few seconds. After testing different phosphors, it was found that pure KBr is highly resistive to the ion beams and gives a strong light for many hours in the beam. The TV technique, in conjunction with slits and pepperpot plates, is also used to measure the emittance of the ECR ion source.

A buncher is placed into the last section of the injection line. We built it together with Tampere Technical University, which was responsible for the high-power sawtooth generator and related electronics. The generator contains electronics for phase and amplitude controls and measurement, a 2×300 W power amplifier, a high-impedance matching unit for the buncher grids and two dummy loads. The buncher is remotely controlled by the control system of the K130 cyclotron. The control system is also used to compute and lock the phases in the buncher. The buncher was installed in May 1992, but its testing is not yet completed.

The vacuum pumping in the injection line is done by turbomolecular and ion pumps which can produce an operating pressure of 5 × 10^{-6} Pa (5 × 10^{-8} mbar).

8. SPIRAL INFLECTOR

The shapes of the spiral inflectors for the $h = 1$ and $h = 2$ modes of operation were determined from analytical formulae. RELAX3D[6] was used to calculate the electric field for the ion-tracking program. The electrodes of the spirals were machined in our workshop by a numerically controlled milling machine.

The spiral deflector is lowered through the hole in the upper yoke by a lifting mechanism. When lowered, the position of the inflector is fixed in the hole of the central region without any mechanical adjustments. Figure 5 shows the central region with short aluminum arms where the dummy dees can be mounted.

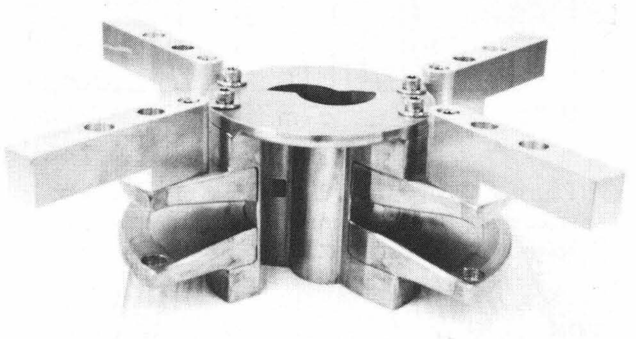

Fig. 5. Photo of the central region.

9. CONTROL SYSTEM

The control system of the Jyväskylä accelerator facility has been previously described in the proceedings of the Berlin-89 cyclotron conference.[7]

The control system is based on ALCONT II hardware from the Finnish company Ahlstrom Automation Ltd (recently sold to the Honeywell Co.). It is a commercial industrial control system based on distributed microcomputers. This system is widely used in process industry (mainly paper and pulp) in Finland. The selection of this particular control system was based on economic and manpower considerations. Only two manyears were needed for programming.

The system has two display units with touch-sensitive 19" screens in the main control room and one in the ECR room.

All software development and system configuring is done with standard 386-based PCs. The PCs are also used for system software loading, backup copying and diagnostics. The ability to load and update application software on-line to the running system has proved to be extremely useful in this kind of application.

The control system hardware was installed in 1990. The final cabling and device connections were made mainly during 1991 parallel with the software development and testing.

10. THE FIRST BEAMS

When the lifting mechanism for the spiral inflector was completed by the workshop in October 1991, everything was ready for the first injected beam in the K130 cyclotron. Then it was decided to improve the water cooling system of the laboratory, which had suffered from many malfunctions and flaws during the first few months of operation. The one-week break promised lasted five weeks in practice.

The first beam was injected into the K130 cyclotron in December 1991 and detected in the main probe in its innermost position. That time there was not enough radiation shielding toward the construction site of the adjacent experimental hall. Further acceleration was therefore not permitted. In the middle of January 1992 this restriction was removed. On January 28, 1992 the 6.0 MeV/u $^{4}He^{1+}$ beam was extracted from the K130 cyclotron for the first time. The extracted current was 120 nA. After a few hours of tuning the extracted current had increased to 330 nA, which gave an extraction efficiency of 55% from a 600 nA internal beam. The transmission through the inflector was 7% from a DC beam, which is only slightly below the theoretical maximum (limited by phase acceptance in the central region).

Beam development has been continued during the spring 1992. In most cases, the $^{4}He^{1+}$ beam has been used for testing. Also a $^{40}Ar^{10+}$ beam at 6.0 MeV/u has been successfully accelerated. In all tests the $h = 2$ mode of operation was used. In June 1992 a spiral inflector for the $h = 1$ mode of operation was available, and during the last days of June of 1992, a 70 MeV proton beam was accelerated up to the full radius.

The first physics experiment using the K130 cyclotron was carried out in June 1992. Positron emitters were then produced with a 55 MeV α-beam in a provisional chamber installed a few meters beyond the cyclotron exit port.

11. LABORATORY BUILDING

The new cyclotron required a new laboratory building. It was built in two phases on a beautiful lake-shore site about two kilometers from the old laboratory. The first phase was started in June 1989 and only included the cyclotron bunker and areas for the ECR ion source, power supplies and the cooling and ventilation systems. It was completed, together with the adjacent workshop and library building, in December 1990. Unfortunately the subcontractor responsible for the water cooling system was badly behind the schedule, so that all cyclotron tests had to be postponed until April 1991.

The accelerator group moved to the new laboratory in February 1991. More than 50 staff members are still waiting for new premises for the Department of Physics, which are expected to be ready in 1994. The quality of life at the site was further upgraded by the opening of a new beautiful bridge connecting the old and new campus areas in summer 1991.

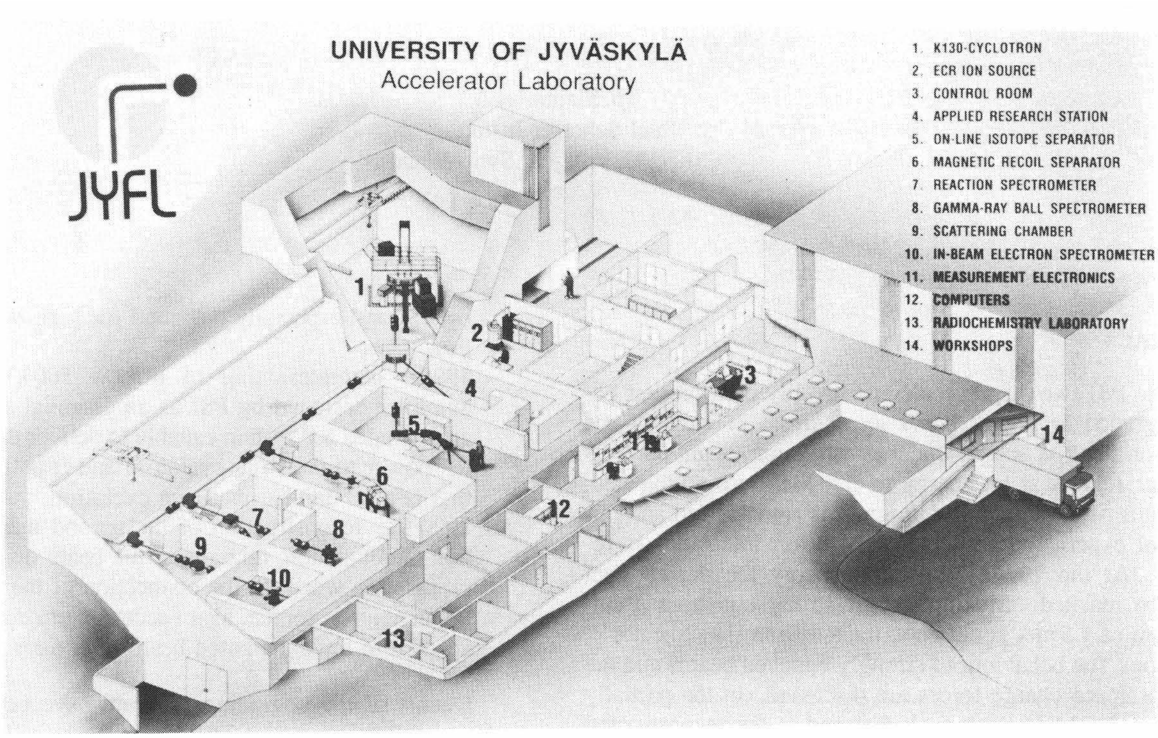

Fig. 6. Lay-out of the laboratory.

The new campus has turned out to be a popular tourist attraction. About 1200 visitors came to see the new accelerator and laboratory in 1991, and about 1800 in the first half of 1992.

The construction of the second phase of the building, which houses the experimental hall, was completed in June 1992. Concrete blocks for radiation shielding in the experimental hall were provided and installed by the construction company. The magnets for the beam lines and the new gas-filled recoil spectrometer were delivered by the Danish company Danfysik A/S in June 1992. The vacuum pumps and other vacuum components for the beam lines were also delivered. Therefore it will be possible to complete the first beam lines and experimental setups in the fall of 1992. The first experiments using the new facility could be run before the end of 1992.

Figure 6 shows the general layout of the new laboratory.

12. REFERENCES

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