COMMISSIONING OF THE COOLER SYNCHROTRON COSY

R. MAIER, U. BECHSTEDT, J. DIETRICH, S. MARTIN, D. PRASUHN,
A. SCHNASE, H. SCHNEIDER, H. STOCKHORST, R. TÖLLE

Forschungszentrum Juelich GmbH, D-52425 Juelich, Germany

COSY Jülich is a cooler synchrotron and storage ring with a proton momentum range from 270 to 3300 MeV/c. It has been conceived to deliver high precision beams for medium energy physics. To accomplish this goal two cooling systems are used. An electron-cooling system that reaches up to a momentum of 645 MeV/c and a stochastic cooling system that covers the upper momentum range from 1500 to 3300 MeV/c. Since its inauguration in April 1993 substantial progress in developing beams for the experiments has been achieved and the physics program has started. Proton beams in a wide energy range have been delivered to internal as well as external experiments.

1 Description of the Facility

The COSY accelerator complex, figure 1, comprises several ion sources, the refurbished isochronous cyclotron, a 100 m long injection beam line, the COSY-ring with a circumference of 184 m, and extraction beam lines to the external experiments[1]. The ion sources are a H_2^+, H^-, and a H^- polarized ion source.

At present the injector cyclotron runs continuously with H_2^+ beams with an energy of 76 MeV. Currents around 10 µA are readily obtained and fed into the accelerator ring via stripping injection. This injection technique has proven to be very reliable. Therefore it was decided to use the same injection scheme for polarized H^- beams as well. Preparations have been made already for the necessary changes in the injection region of the ring.

At present extraction beam lines guide the beam to three external experiments. One site being the large magnetic spectrometer BIG KARL, the other the Time of Flight facility (TOF), and the third is foreseen for experiments with low proton momenta (800 MeV/c). A fourth beam line is foreseen for experiments needing longitudinal polarization.

The COSY-ring has a race track design with 40 m long straight sections. Sixteen quadrupoles in each section grouped as four triplets allow the ion optics to be tuned such that the sections act as telescopes with a 1:1 imaging giving either a π or a 2π phase advance. At the same time optimized beam conditions for the internal experimental stations TP1 and TP2 can be adjusted. Meanwhile, the EDDA-experiment[2] went into operation at target point TP2. While one straight section has been designated to serve the experiments the other one contains accelerator specific components like the accelerating rf-cavity, the electron cooler, scrapers, Schottky pick-ups, and current monitors.

The arc sections have a length of 52 meters each. They are composed of three identical elements that have in themselves a mirror symmetry. A half-cell has a QF-bend-QD-bend structure with the option to interchange focusing-defocusing for added flexibility in adjusting the tune. This structure leads to a six fold symmetry for the total magnetic lattice of the ring. Stripping target and bumper magnets for injection and electrostatic and magnetic septum for extraction are located in one arc-section.

Table 1: Basic COSY Parameters

Vacuum system	
pressure range:	10^{-10}-10^{-11} mbar
shape of vacuum chamber:	
in the arcs	rectangular 150-60 mm^2
in the straights	circular, ø150 mm
RF system	
cavity type/ acceleration structure	symmetric re-entrant ferrite loaded
frequency range (h=1)	0.462-1.572 MHz
quality factor (at frequency)	8 (400 kHz), 40 (2 MHz)
max. rise in frequency	4 MHz/s
gap voltage (at duty cycle)	5 kV (100%), 8 kV (50%)
gap voltage dynamic range	55 dB
nominal/actual rf power	56/16 kW in Push-pull
Bending magnets	
number	24
radius	7 m
angle	15°
field range	0.23-1.585 T
Quadrupole magnets in the arcs	
number	24
no. of families	6
eff. length	0.3 m
aperture radius	85 mm
max. gradient	7.5 T/m
Quadrupole magnets in the telescopes	
number	32
no. of families	8
eff. length	0.55 m
aperture radius	85 mm
max. gradient	7.5 T/m
Sextupole magnets	
number	18
no. of families	7
eff. length	0.3/0.2/0.1 m
aperture radius	85 mm
max. gradient	30 T/m^2

Besides the diagnostic kickers and the elements for the ultra slow extraction the other arc-section contains the internal target station TP3 where the COSY-11 experiment has been installed recently. This target station uses one of the ring's bending magnets to separate ejectiles around zero degree from the circulating beam and is thus well suited to study physics close to particle thresholds. At the connecting points where the arc sections meet the straight sections the stochastic cooling pick-ups and corresponding kickers will be built in. A detailed review on the diagnostic tools in COSY is given on this conference[3].

Table 1 summarizes the fundamental parameter set of the COSY-ring and figure 1 presents the whole facility.

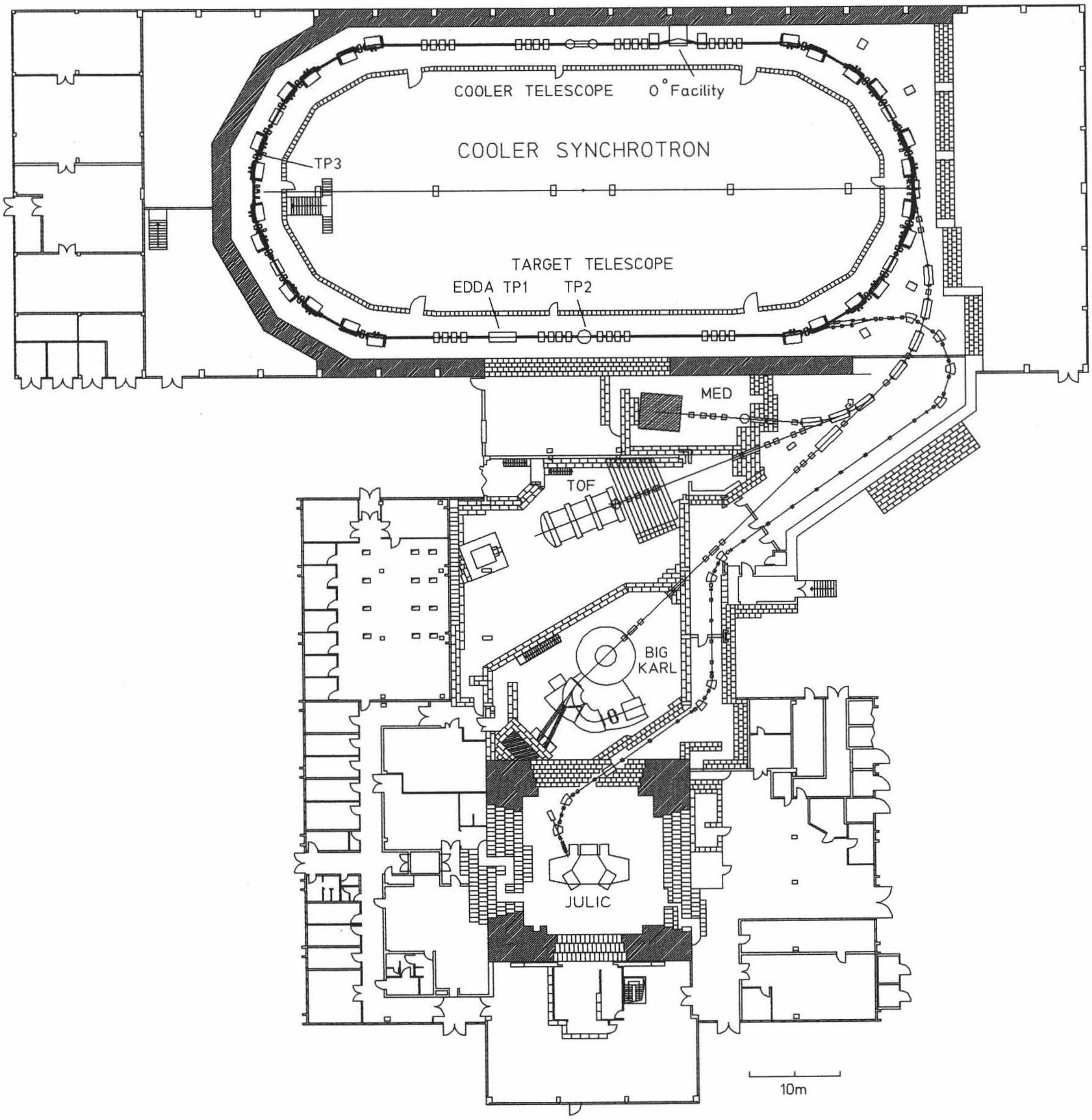

Figure 1: Floor plan of the COSY facility

1.1 Ion Sources

At present a H_2^+ source is being used with stripping injection into COSY. It has demonstrated reliable operation together with the injecting cyclotron. As there is a strong demand for polarized beams a polarized source has been developed. The stripping injection will be kept for its high efficiency and ease in operation. Therefore, the decision fell towards a H^- polarized source after successful tests had been performed accelerating H^- with the cyclotron. Meanwhile a separate H^- unpolarized ion source has been installed and beam currents up to 10 μA have been extracted from the cyclotron. In future operation when the stripping area has been modified only H^- will be used for unpolarized and polarized beams. This will allow for fast switching between polarized and unpolarized beams without changes to the cyclotron, the injection beam line, or the stripping region of COSY.

The polarized ion source has been mounted at the injection beam line to the cyclotron and went through its first testing stage. Thus far beam currents of about 1 μA H^- in the injection beam line to the cyclotron were obtained with estimated polarization values larger than 75%. Optimizing parameters, e.g. raising the cesium beam energy from 20 kV to about 50 kV will increase the beam current by nearly a factor of ten. Better focusing of the Cs-beam and raising the atomic beam intensity give addition potential for higher beam currents[1].

1.2 Cyclotron Injector

For higher system performance and reliability major components of the old JULIC cyclotron had been replaced like the RF-Generator and the trim coils. Since its recommissioning the cyclotron has been operating with very high reliability as an injector. The machine working now on a single energy opened the opportunity to study various parameters over long time periods with high precision. The main field is meanwhile stabilized with a NMR-signal using a PC in the feedback path that computes small correcting currents and feeds them separately to six extra windings parallel to the main coils. A field stability of $1 \cdot 10^{-6}$ is obtained with this kind of regulation and automatically monitored and documented over long time periods. A detailed review is given in this conference[4].

2 Internal Experiments

There is a very intimate relation between internal experiments and the accelerator as they affect each other in a direct way. As mentioned before EDDA[2] is an internal experiment at TP2 that has been set up to measure excitation functions with high precision. A new insight into hadron-hadron interaction is expected if minute anomalies were found. The basic design is a thin horizontally oriented fiber target that intercepts the beam combined with a cylindrical detector system surrounding the thin walled beam pipe. Due to its construction the EDDA experiment is not only a tool for medium energy physics but also an excellent probe for investigating and verifying beam properties of COSY with high precision.

This experiment has special requirements on the beam to achieve optimal measurement conditions. This concerns the lateral stability and the orientation of the phase space ellipses. It is the latter point where the flexibility of the target telescopes proved invaluable. Figure 2 shows relevant parameters of an early run. Four parameters versus time are combined in this picture.

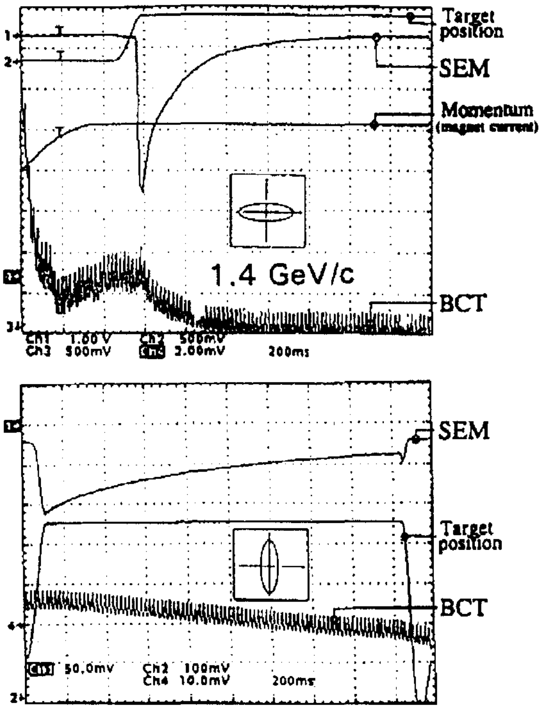

Figure 2: Beam current on the internal target measured with SEM

One horizontal division corresponds to 200 ms. The vertical scale shows the parameters under measurement converted to a voltage with an arbitrary scaling and offset. Curve 2 gives the vertical position of the fiber target. It rests underneath the beam and is moved into the beam at a fixed time. Curve 1 shows the secondary electron current which steeply rises the moment the fiber dives into the beam. The current then gradually fades away proportional to the diminishing beam as particles get scattered outside the ring's acceptance. The circulating particles are monitored with a beam current transformer (BCT) as shown in the lowest curve. The curve labeled momentum is derived from the magnetic dipole fields. As depicted the target was moved into the beam shortly after the flat top of the beam momentum had been reached with 1.4 MeV/c. A beam live time of 160 ms can be deduced from the curves. Although this value was fine for the first data taking, the rush of data was hard to handle by the computers. Therefore, the experimenters liked to see a much longer life time.

The key to this goal is found in the small ellipse shown in this picture. This ellipse represents a cross section through the beam at the target position. The large horizontal extent was less optimal for the horizontally stretched 5 μm carbon fiber. By changing the settings of the straight section the ellipse was rotated by 90 degree shown in the picture underneath yielding a significantly better behavior. The time scales are identical.

It is important to note that this change was virtually transparent to the rest of the ring's ion optics. At the top you find the SEM signal, the bottom curve is the BCT signal. The target position is seen in the middle. The important figure to note is the beam life time which has been extended by more than a factor of five to 870 ms. This dramatic increase in beam life time meant a real breakthrough for the experiment, relieving the data acquisition from the high peak count rate it had to deal with before. The carbon fiber that was used during these measurements was needed to estimate background reactions produced when using a polyethylene (PE) fiber to investigate p-p interaction. With a somewhat thinner PE-fiber beam life times of 2.7 s have been reached meanwhile.

In the plots shown before the target had been moved into the beam while the momentum had reached the flat top. But this experiment's goal is to measure excitation functions which means that it needs to take data while the machine is ramping up the energy. This requirement puts high demands on the machine's parameter stability during the time these parameters are synchronously changed to reach the flat top. Recent studies however have shown that during data acquisition in the ramp no variations were found that did hint a temporary instability on the side of the machine. The result is plotted in figure 3 with the horizontal scale being 50 ms/div. The important difference compared with the upper plot in figure 1 is, that the target was moved into the beam while the machine was ramping up, thus covering a momentum range from 786 to 1131 MeV/c. This beam stability fulfills an important prerequisite for the upcoming precision investigations of EDDA. The longer life time available now will certainly ease the task of scanning a broader momentum range.

Proton-proton elastic scattering excitation functions in the kinetic energy range 0.5 to 2.5 GeV have been successfully measured[2]. The data were taken while ramping up the energy to flat top energy. The quality of the data proves the machine's parameter stability even while ramping.

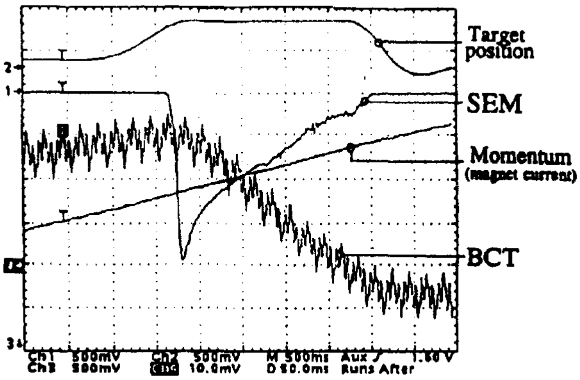

Figure 3: Beam on the internal fiber target during ramping

In the middle of 1995 first experiments of COSY 11 have been started. This experimental facility[5] has been designed to study production, internal structure, and decay of mesons as well as meson-nucleon and meson-meson interactions. For this reason a cluster target is placed in front of a C-type dipole magnet in which a modification of the vacuum chamber became necessary so as to contain an extraction window for the reaction ejectiles. Back-leg windings are used to compensate eddy currents in the thick walls of this large vacuum chamber during ramping up the energy. Proton-proton and proton-deuteron scattering meson production will be measured and the reaction ejectiles will be determined via a set of drift chambers and scintillation counters. The interaction should be studied close to the production threshold with the emphasis on the meson mass range around 1 GeV/c^2. First measurements have been done successfully for the production of η mesons and the mesonic $\pi^+\pi^-$ system.

In many synchrotrons it is unavoidable to cross transition energy[6] during acceleration. In the vicinity of this energy, completely determined by lattice functions, the circulating bunched beam may become highly unstable, especially at high beam currents and tiny bunches. In a recent machine experiment the flexibility of the COSY-lattice was proven which allows a shift of the transition point upwards during acceleration. In flat top the rf-voltage was then adiabatically turned off, and after debunching the transition energy was reduced to its nominal value giving the desired dispersion in the straight sections. After that the beam could be rebunched nearly without losses. The downwards shift of transition energy was clearly visible in a 180^0 rf-phase jump as shown in figure 4. The upper two traces show the radio frequency and the circulating bunch after reaching flat top energy. The lower two traces show radio frequency and bunch after recapturing. It should be noted that this manipulations can be done without changing the machine's working point.

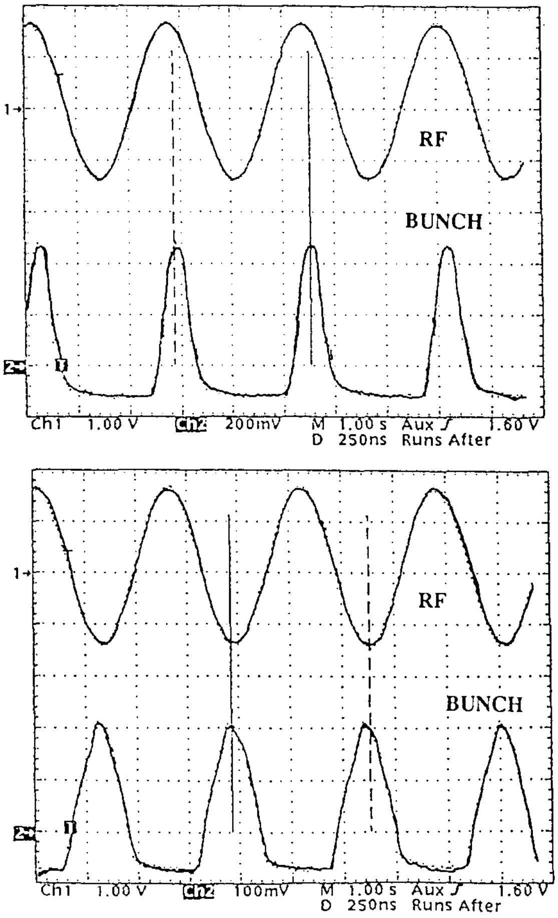

Figure 4: Transition energy shift in flat-top

3 External Beams

Up to now conventional resonant extraction is used to serve external experiments. Beams with momenta ranging from 270 to 1030 MeV/c have been delivered to three experimental collaborations. In particular for experiments that measure close to threshold beams with precisely defined energies have been extracted as in the case of the $p+p \rightarrow d+\pi^+$ reaction. External experimental stations have also been used for pre-therapeutical studies.

Figure 5 shows a plot demonstrating the behavior of the machine's principal parameters during resonance extraction with a time scale of 1 s/div. The upper trace shows the extracted current measured with scintillator paddles in the external beam line. An overall spill time of about 2 s was reached in this example. Below this is the sextupole ramp under which the extraction bump in the closed orbit is visible with a similar shape but starting a little earlier. The trapezoidal structure with points down is the RF-signal. The RF is adiabatically switched off shortly before extraction to avoid any residual time structure that would otherwise reduce the overall duty factor of the external beam. The trace with the needle like peak at the beginning is the current measured with the BCT. At this peak the machine is filled with protons at injection energy. Catching the particles with the RF reduces the current as seen in the first minimum.

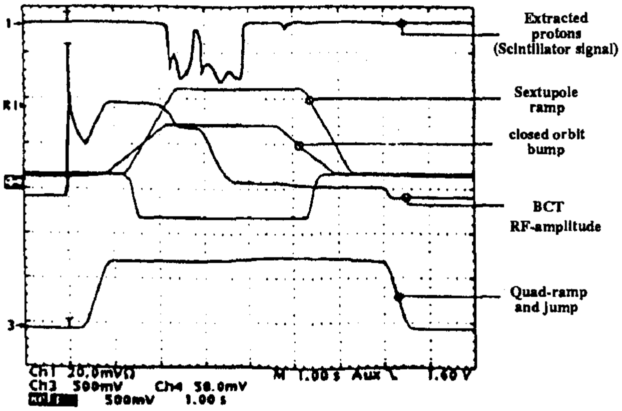

Figure 5: Machine parameters during extraction

Accelerating the beam cranks the current up due to the higher revolution frequency until the plateau is reached. Shortly after, the ramps to initiate the extraction start. The bottom curve shows the current in the ring's arc quadrupoles. Opposed to ordinary storage operation the current in the plateau is not kept constant but raised with a mild slope to force the circulating particles into resonance.

The horizontal and vertical beam spot at the TOF target station at 1030 MeV/c was measured with a silicon microstripdetector, figure 6.

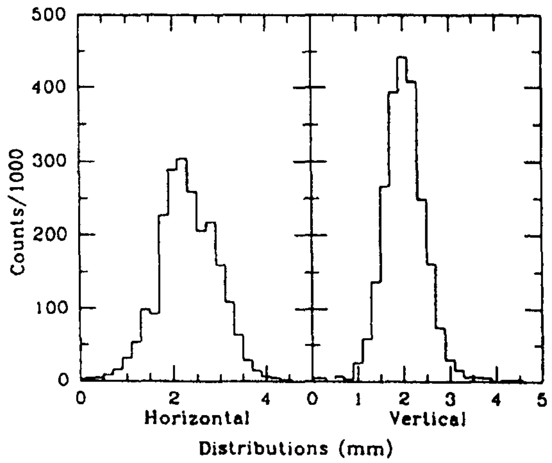

Figure 6: Horizontal and vertical beam spot size at the TOF target

The strip width was 200 μm. Although no cooling had been applied in this case we found a machine setting giving a FWHM close to 1 mm in both directions which was very advantageous for the experiment. At present up to 10^9 protons per second in a spill time of 1 s with a repetition time of 7 s can be extracted.

4 Cooling the Beam with Electrons

In February 1993 the electron cooler was moved from its test site into the ring. For the first time cooled protons circulated on May 25th 1993 in the COSY-ring. The voltage of the e-cooler was set at 20660 V corresponding to an injection energy of about 38 MeV. The electron current was 0.25 A and the ring contained about 10^9 protons with the rf running at the corresponding frequency and an amplitude of 500 V. The shrinking of the longitudinal phase space was clearly seen in the reduced width of the sum signal of the beam position monitors (BPM) after ca. 3 s. Schottky noise of the coasting beam was picked up from which one could deduce the momentum spread of the beam which was reduced by a factor of ten from 10^{-3} to 10^{-4} for $\Delta p/p$. Further, H^0-diagnostic has been applied to measure the transverse emittance. H^0-particles are formed in small quantity inside the electron cooler and fly forward undisturbed by magnetic fields. They were picked up with a wire chamber 25 m downstream of the e-cooler behind the first ring dipole. This tool made for the first time also the transverse cooling process in COSY visible and allowed to study the dynamic behavior. The distributions obtained as a function of time can be seen in figure 7. A reduction from about 25 π mm mrad down to 0.4 π mm mrad was observed after 6s of cooling.

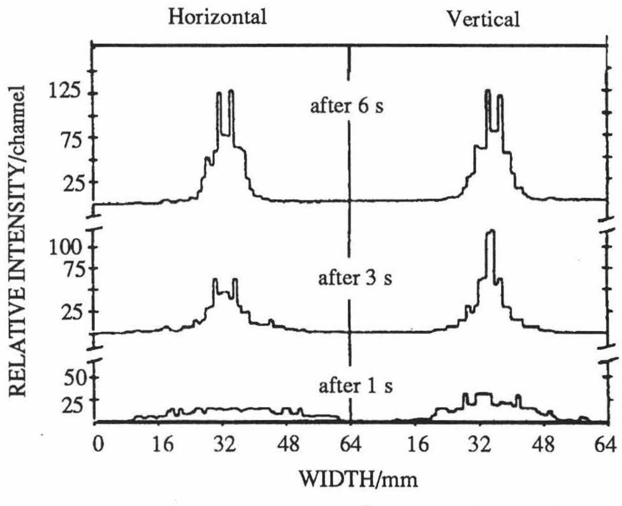

Figure 7: Horizontal and vertical H^0-spectra of the cooled beam

In order to achieve these results the proton and electron beam directions had been adjusted to better than 0.3 mrad by using proton correction steerers and the quadrupoles in the cooling telescope to compensate magnetic disturbances of the cooler magnets to the storage ring.

5 Stochastic Cooling

The stochastic cooling is using a two band RF-system (1 - 1.8 GHz; 1.8 - 3 GHz). The gap width of the ultra cold pickup electrodes as well as of the kicker electrodes can be adjusted according to the beam size to get maximum sensitivity. All active components of the RF signal path are available meanwhile. A programmable delay is used that will allow to cool over an energy range from 0.8 to 2.5 GeV. Prototypes of critical components inside the cooling tank have already been tested and optimized. One horizontal and vertical pick-up tank of band I (1 - 1.8 GHz) are now installed in COSY for test measurements. The electrode bars are cryogenically cooled down to about 30 K to achieve a good signal-to-noise ratio even for low particle numbers in COSY.

A horizontal Schottky-spectrum taken near the 744th and 745th harmonic of the revolution frequency f_0 = 1.47835 MHz, corresponding to a flat top momentum $p \approx 2.2$ GeV/c, is shown in figure 8. Approximately $2 \cdot 10^{10}$ protons were stored at flat top energy. The spectra were taken with 1 kHz resolution band width.

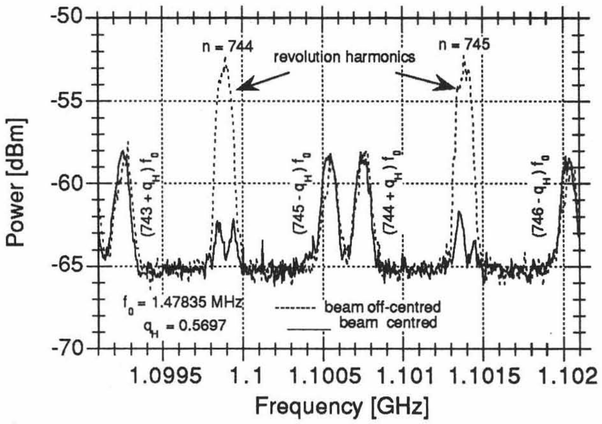

Figure 8: Horizontal Schottky-spectrum

The figure clearly demonstrates the good signal-to-noise ratio for the betatron sidebands as indicated in the figure. The dotted spectrum additionally shows the revolution harmonics due to an off-centred pickup with respect to the beam. These lines can be strongly reduced by a parallel shift of the electrode bars, except a contribution, which is double-peaked near the revolution harmonic and drops at the centre of the harmonic (full line). This structure can be explained by a finite dispersion of the machine at the location of the pickup and also depends on the root mean square of the momentum spread of the particles. The horizontal spectrum thus may also contain information on the longitudinal beam distribution. This can be utilized for longitudinal cooling as was first pointed out by Palmer[7]. Note, that the sidebands are not affected (full line) by a parallel shift of the electrode bars. In further experiments the sensitivity will be optimized by properly adjusting the gap width of the electrode bars.

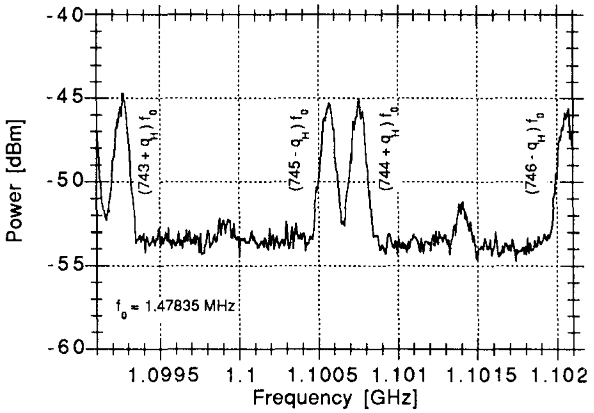

Figure 9: Vertical Schottky-spectrum

The horizontal tune, determined from two sidebands, agreed with the value $q_H = 0.5697$ found with a resonant Schottky pickup. The width (4σ) of the revolution harmonic $n = 744$ is $\Delta f = 140$ kHz. Assuming a frequency slip factor $\eta = 0.16$ one can derive the width (4σ) of the relative momentum spread distribution to be approximately 0.8‰.

The corresponding vertical Schottky spectrum is shown in figure 9. In this case no double peaks near the revolution harmonics are visible due to the absent dispersion. From the figure one can conclude that the vertical tune is almost the same as in the horizontal plane.

6 Summary and Outlook

The cooler synchrotron COSY has shown reliable operation and a steady growth in beam quality, energy and intensity. The final energy could be extended to the design energy of 2.5 GeV. Proton numbers up to $3 \cdot 10^{10}$ could be accelerated. The machine has now reached a point where the experimental program can progress with its intended measurements. The future will be marked by bringing components like the ultra slow extraction into operation and installing systems like further elements for stochastic cooling. This holds also for experiment specific parts. A machine development program has been set up that will continue to improve our handling and understanding of the machine. On this path the raise of the extraction efficiency and duty factor have been given high priority to further exploit the machine's potential for medium energy physics.

At present considerable work is done for a new device for experiments at internal targets, the 0^0 facility ANKE [8], to study nuclear medium effects, e.g. in the subthreshold K^+ production in proton-nucleus reactions and in the proton-induced deuteron breakup. The realization of the facility, for which three additional large dipole magnets will be installed in the COSY ring, made progress in the completion of the concept studies and in the begin of construction. The development of the detector systems has been continued. Studies on a polarized target, the fast trigger electronic system and on reaction estimates are still going on. The 0^0 facility will be located between two triplets of the cooler telescope as indicated in figure 1.

References

1. R. Maier et al., "Status of COSY", Proceedings of the Fourth European Particle Accelerator Conference, London (1994)165, and references therein
2. J. Bisplinghoff et al., AIP Conf. Proc. 221, Am. Inst. of Phys. 1990 p. 312
   Physica Scripta **48** 1993 p. 92
   Annual Report 1994, Institut für Kernphysik Jül-3035, p. 23
3. J. Dietrich, Recent Beam Diagnostic Techniques, this conference
4. W. Bräutigam and R. Brings, Beam Stabilization by Feedback Control of the Accelerating Parameters in a Cyclotron, this conference
5. D. Gronzka et al., Proceedings of the Int. Conference "Physics with GeV-Particle Beams", Forschungszentrum Jülich, Aug. 22-25, 1995, to be published in World Scientific Publishing Co. Pte. Ltd.
6. K. Johnsen, "Transition", CERN ACCELERATOR SCHOOL, CERN 85-19, p. 178
7. D. Möhl, G. Petrucci, L. Thorndahl and S. van der Meer, Phys. Rep. **85/2** (1980)
8. K. Sistemich et al., Status of the 0^0 Facility, Annual Report 1994, Institut für Kernphysik Jül-3035, p. 41