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Beam diagnostic developments at the cooler synchrotron COSY-Jülich

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Abstract. New developments of beam diagnostic devices and methods at the cooler synchrotron and storage ring COSY at the Forschungszentrum Jülich are described. A Schottky-pickup was tested and installed. The new pickup consists of four diagonally arranged plates which can be combined by means of relays to measure either in the horizontal or in the vertical plane. A new method for resonant tuning of the Schottky-pickup for transversal measurements was realized. A tune meter was developed for real-time tune measurements in the acceleration ramp and is used as routine diagnostic tool. Based on the developed bunch synchronous tracking generator an on-line phase space measurement was realized. For beam profile measurements a residual-gas ionization beam profile monitor was installed in the COSY-ring and tested. To measure the beam quality in case of fast and slow extraction a universal spill detector was developed and tested in the extraction beam line.

Keywords. Beam diagnostic; synchrotron; beam profile measurements.

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1. Introduction

The COSY accelerator facility, shown in figure 1, is depicted in detail in [1–4]. Briefly, it consists of two sources for unpolarized H^-/D^- ions and one for polarized H^- ions, the injector cyclotron JULIC that accelerates the H^- ions up to 300 MeV/c and D^- ions up to 600 MeV/c and the cooler ring COSY with a circumference of 184 m accelerating the protons and deuterons up to 3.4 GeV/c. Injection into COSY takes place via charge exchange of the negative ions over 20 ms with a linearly decreasing closed orbit bump at the position of the stripper foil. The polarized source presently delivers 10 μA of polarized H^- ions. Four internal target areas [1,2] are available for experiments with the circulating beam. The beam can also be extracted via the stochastic extraction mechanism and is guided to three external experiment areas [1,2]. Recently, fast kicker extraction [5] has been tested, which is essential for the new experiment JESSICA. The phase space density of the protons in COSY is improved by electron and stochastic cooling [3]. The zero-degree-facility ANKE is now routinely in operation [2].

Beam diagnostic at the COSY facility can be divided into three regions: injector (ion sources isochronous cyclotron JULIC and injection beam line), COSY-ring (synchrotron and storage ring) and extraction beam lines to the external experiments. In each region there are different beam parameters like current, time structure, momentum. Correspond-

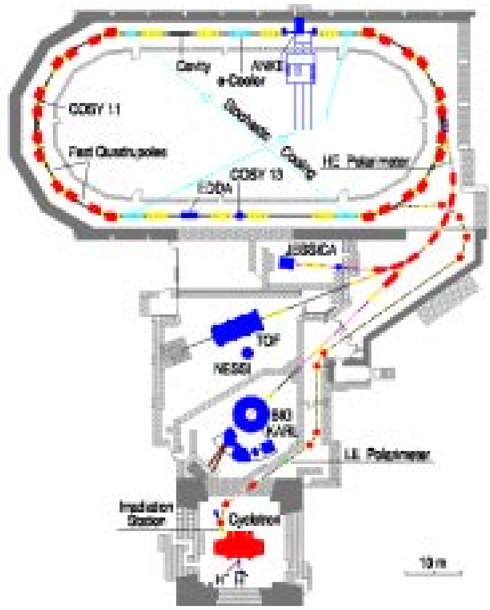

Figure 1. Floor plan of the COSY accelerator facility.

ing different diagnostic devices are used to measure beam properties. In the following some recent developments in the field of diagnostics are described.

2. Schottky-pickup

The original 1 m long Schottky-pickups had to be removed mainly to gain space for new installations (rf-cavity, experimental devices), but also to increase the horizontal aperture. The available space for the new pickup is only 0.8 m. The pickup can be used either as a sensitive broad-band beam position monitor or as a tuneable narrow-band sensor for Schottky-noise analysis with ultrahigh sensitivity. A new method for resonant tuning of the Schottky-pickups for transversal measurements was developed [6]. The differentially excited resonant circuitry enhances the sensitivity by about a factor of 30. The pickups are also used for dynamic tune measurements (tune meter) in the acceleration ramp [7]. The capacitive monitor with high impedance preamplifier has the particular advantage of a flat frequency response within a pass band. The lower cut-off frequency is determined by the electrode capacity and the preamplifier input impedance, and can be realized to 10 kHz. The upper cut-off frequency is determined by the band width of the preamplifier and is larger than 100 MHz. The transfer impedance is maximized if all the electrodes together entirely enclose the beam. For high sensitivity the electrode capacity C_{el} must be small, i.e., the distance to the beam tube should not be made too small. Therefore, the vacuum tube should rather be enlarged and the electrodes positioned in extension of the beam tube. Important for the transversal signals is the coupling capacity C_{c} between the electrodes that reduces the amplitude. C_{c} must be small in comparison to the electrode capacity. This also means that the electrode capacity cannot be made as small as possible.

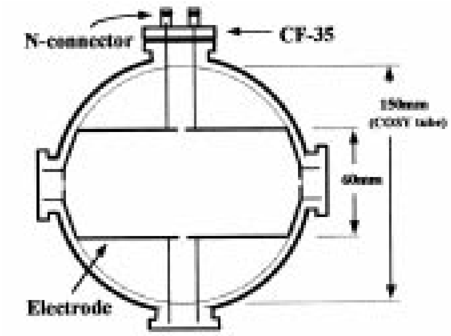

Figure 2. Lay out of the new Schottky-pickup for measurements in horizontal and vertical plane (after proper switching of coax-relays).

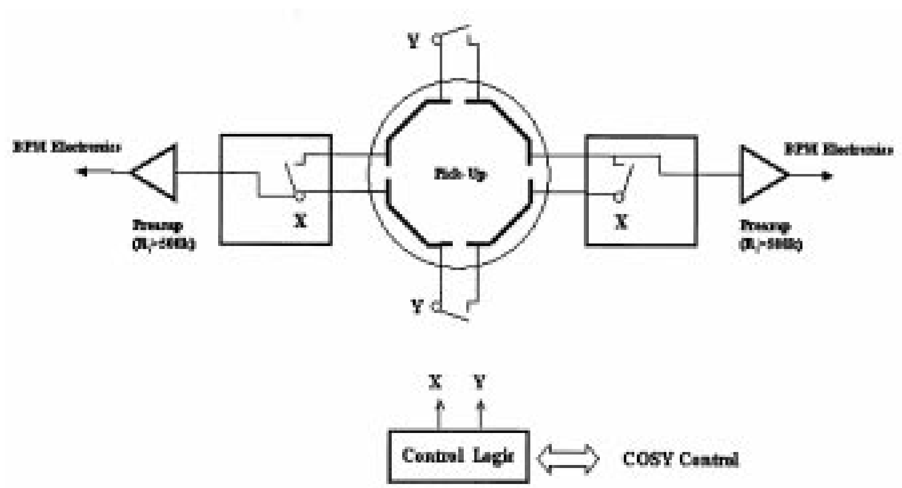

Figure 3. Broad-band application of the Schottky-pickups.

The geometry of the new Schottky-pickup has the schematic lay out shown in figure 2. Horizontal and vertical apertures of 150 mm and 60 mm respectively were chosen. The structure is split into four electrodes that together surround the beam. To achieve a small coupling capacity (e.g. $C_c > C_{el}/10$), the separating slits cannot be made too narrow, thus an azimuthal coverage of about 95% must be tolerated. The pickup electrodes can be combined by means of relays for horizontal, vertical or longitudinal broad-band measurements as is shown in figure 3.

3. Dynamical tune measurement

A tune meter was developed for real-time tune measurements in the acceleration ramp [7] and is used as routine diagnostic tool. Especially in the case of acceleration of polarized protons the dynamical tune measurement in the ramp is very important for correction of the vertical tune dependent intrinsic resonances (depolarizing resonances). A band-limited

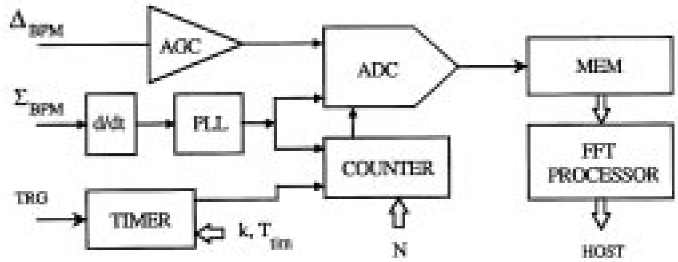

Figure 4. Block diagram of the FFT tune meter.

broad-band noise source was used for beam excitation. The transversal beam position oscillation was bunch-synchronous sampled and digitized with a high resolution ADC. The Fourier transform of the acquired data represents immediately the betatron tune.

3.1 *Tune meter configuration*

Via the strip-line unit, coherent betatron oscillations in horizontal and vertical direction can be raised by means of broad-band transversal excitation. The cumulative effect of subsequent excitations on the circulating beam results in a coherent oscillation at resonance frequencies only. Other components of the excitation are neutralized and therefore have virtually no effect on the beam. A white noise source generates the exciting signal. A band-pass filter with fixed cutoff frequencies (BW = 100 kHz to 2 MHz) limits the excitation band width. The frequency range of the noise always covers at least one betatron side band at the fundamental frequency over the whole ramp without frequency feedback. The excitation can be enabled/disabled by means of a fast GaAs switch that is controlled by either remote commands or a timer unit. The programmable excitation level changes in real-time. A beam position monitor (or Schottky-pickup) picks up the beam response on the excitation. Low noise gain controlled amplifiers determine the level of the sum and difference signals. The bunch-synchronous pulse required for the sampling is derived from the sum signal of the same BPM (or Schottky-pickup). A phase-locked loop with narrow-band loop filter generates the clock pulse with low tracking jitter over the whole range between injection and flat top. With proper signal processing, the clock generator tracks also the synchrotron oscillation. For investigations of the synchrotron oscillation, a signal proportional to the synchrotron oscillation can also be derived from the tracking circuitry of the clock generator. A high resolution ADC digitizes the difference signal. The timers of the measurement trigger and of the excitation gate are synchronized. figure 4 shows the block diagram of the FFT tune meter.

3.2 *Signal and data processing*

The betatron oscillation appears as an amplitude modulation on the beam position signal evoking double side bands around each harmonic of the revolution frequency and also around dc in the spectrum of the position signal of the bunched beam. The peak value of the BPM difference signal is proportional to the beam position and can be sampled by means

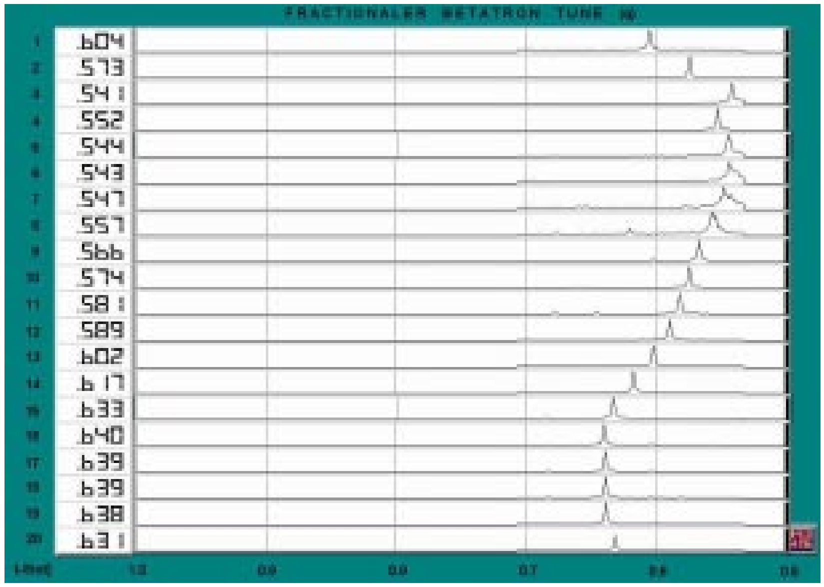

Figure 5. Display of a tune measurement in the ramp consisting of averaged FFT spectra.

of a fast sample and hold circuitry and digitized with a high resolution ADC. The positive edges of the bunch-synchronous clock start the sampling at the bunch peaks, i.e., at the highest betatron amplitude. The gain controlled amplifiers allow an optimum utilization of the 14 bit ADC. The peak value of subsequent bunches carrying the betatron oscillation are recorded. The Fourier transform of this array gives the fractional betatron tune q. This method combines the functions of a synchronous demodulator and a frequency normalizer. Due to the bunch-synchronous sampling, the frequency components of the synchrotron oscillation are suppressed. The sampled data therefore contain mainly the betatron sidebands transposed into the range between dc and $f_0/2$ ($f_0 =$ revolution frequency). The lowest normalized frequency is zero (dc component), the highest usable one is $f_0/2$ and the corresponding range of q or $(1-q)$ falls between 0 and 0.5. Whether the measured value represents q or $(1-q)$ depends on the machine lattice. Subsequently acquired spectra with the same time intervals are displayed as a waterfall diagram (figure 5) showing the tune as a function of time. On the left edge of the screen the values of the detected tune peaks are also numerically displayed.

The beam rigidity is low in the lower energy range. Therefore very weak excitation is adequate for a distinct betatron response. The excitation strength in the ramp has to be increased. Hence the excitation level is programmable as a function of time. It is held as low as possible for an optimum signal-to-noise ratio with minimum particle losses. For this reason the excitation is switched on only for the duration of the data acquisition by means of a fast GaAs switch. The data are taken in blocks of N data words each and stored sequentially in memory. To start the process the COSY timing system triggers an internal timing logic which in turn generates k timing pulses with constant time interval for k tune values. The number k of timing pulses and their interval must be properly chosen to cover the tune measurement time overlapping the total acceleration ramp time as desired. In one data acquisition cycle, $k \times N$ samples corresponding to k tune values are sequentially acquired. These data blocks are transformed by FFT resulting in frequency spectra with $N/2$ data points. As the duration of the acquisition depends on N, its value must be properly chosen, because it also determines the frequency resolution of the FFT spectra (equal to $1/NT$ with $1/T = f_S = f_0$). Although the duration changes in the acceleration ramp, the resolution of the tune $(1/N)$ remains constant. The larger the quantity of the samples is in the array used for evaluation, the higher the frequency resolution will be and consequently also the accuracy of the tune measurement. The average acquisition time $(N \times T)$ for a tune resolution of 5×10^{-3} is less than 2 ms. The transformation of a record needs 35 ms in the used configuration, thus real time tune measurements can be carried out with a frequency up to 25 Hz. With fast FFT processors or with stored records and off-line processing, equivalent rates above 500 Hz can be achieved. To improve the noise floor, the spectra can be averaged. A graphic and numeric display shows the tune as a function of time.

4. On-line phase space measurement with kicker excitation

A new method for on-line phase space measurements with kicker excitation at COSY was developed. The position data were measured using analogue output of two beam position monitors (BPMs) and directly monitored on a digital storage oscilloscope with external clock (bunch-synchronous sampling). Nonlinear behavior of the proton beam was visible as well as resonance islands. The knowledge of the phase space near the electrostatic septum is essential for optimization of the resonant extraction process and very useful for beam dynamics experiments.

4.1 *Experimental set up*

The experimental procedure starts with exciting the beam particles to collective transverse (in our case only horizontal) oscillations with betatron frequency by a fast diagnostic kicker magnet in the COSY ring. The beam bunch is short-time deflected (0.75 μs–2 μs width, rise and fall time >1 μs) and the resulting bunch oscillations are measured using the beam position monitors (BPMs). The kicker excitation is synchronized with the COSY-rf signal and can be adjusted in time by programmable delay, so that a single deflection of the total bunch can be performed (bunch-synchronous excitation). The amplified and filtered sum and difference signals from the BPM electrodes are digitized by flash ADCs (20 MHz clock rate), stored in FIFO memories (4 K or 64 K width) and transferred to files. Depending on the FIFO width, data of about 200 or 3200 successive turns can be stored. Up to now the phase space was calculated from the raw data of two BPMs and MAD calculations for TWISS parameters (α, β, γ) [8]. Now a new method has been developed. The position data are measured using the analog output of two BPMs and directly monitored on a digital storage oscilloscope. The sum signal of a BPM is used to detect a passing bunch. The signal is differentiated and fed into a PLL circuit. The differentiated sum signal has a zero crossing at each bunch peak, nearly independent of the bunch shape and the bunch frequency. The phase loop tracks the zero crossing point and generates a clean, jitter-free clock pulse in phase with the bunch peak (figure 6). The output signal controls the sampling

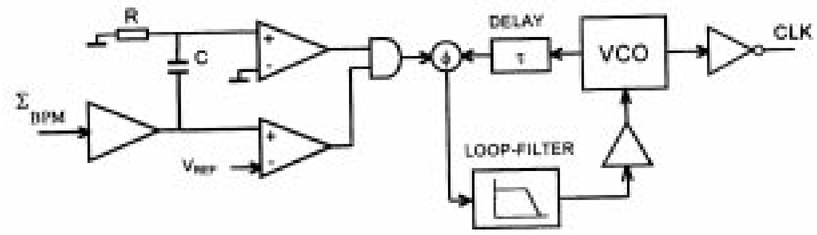

Figure 6. Bunch-synchronous tracking generator.

of the oscilloscope input stages (external sampling clock). Two BPM difference signals are displayed online in the *xy*-display mode. The time of flight between the two BPMs is compensated by an electrical delay. The display represents the position of one BPM vs. the other (except the calibration). To get the phase space diagram (angle x_1' vs. position x_1) the transfer matrix between the two BPMs must be known. Another representation uses the normalized momentum $p_1 = \alpha \cdot x_1 + \beta \cdot x_1'$ vs. position x_1 (canonical coordinates x_1, p_1). If the phase advance between the two BPMs is equal to $\pi/2$, the following expression for the normalized momentum p_1 is found:

$$p_1 = \sqrt{\frac{\beta_1}{\beta_2}} \cdot x_2.$$

That means monitoring x_2 vs. x_1 is similar to p_1 vs. x_1 except the factor $(\beta_1/\beta_2)^{1/2}$.

4.2 *Experimental results*

A problem for such measurements is the 'damping' of the oscillations due to the finite betatron frequency spread of the particles. Typically about 100 oscillations are seen in the present case. To overcome this problem the measurements were performed with a cooled beam. Figure 7 shows the on-line horizontal 'phase space' plot (difference signal BPM_{x24} vs. difference signal BPM_{x22}) near a third-order resonance for four different kick strengths (deflection angles) with an electron-cooled beam (approximately $5{\cdot}10^9$ circulating stored protons, momentum 1.675 GeV/c). Under these conditions more than 40,000 oscillations could be observed. The momentum deviation $\Delta p/p$ is about $2{\cdot}10^{-3}$ before and $1{\cdot}10^{-4}$ after cooling the beam. A sextupole (nonlinear) magnetic field is used to excite the third-integer resonance (in this case the horizontal tune amounts $Q_x = 11/3$). The effect of nonlinearity makes the tune increase with increasing kick amplitude, and so there is one amplitude for which the tune is exactly 11/3. Furthermore, there is a frequency entrainment effect causing all nearby amplitudes to lock-on to exactly the same tune. This accounts for the existence of so called resonance islands [9]. When the beam is kicked with a small amplitude the particles are not kicked upon the resonance. At a certain amplitude the 'lock-on' is visible and islands are formed (see figure 7). During the first 100 turns the motion is damped before the particles are trapped in the island. The particles jump to another island each turn and return to the starting island after three revolutions. The bunch within the island

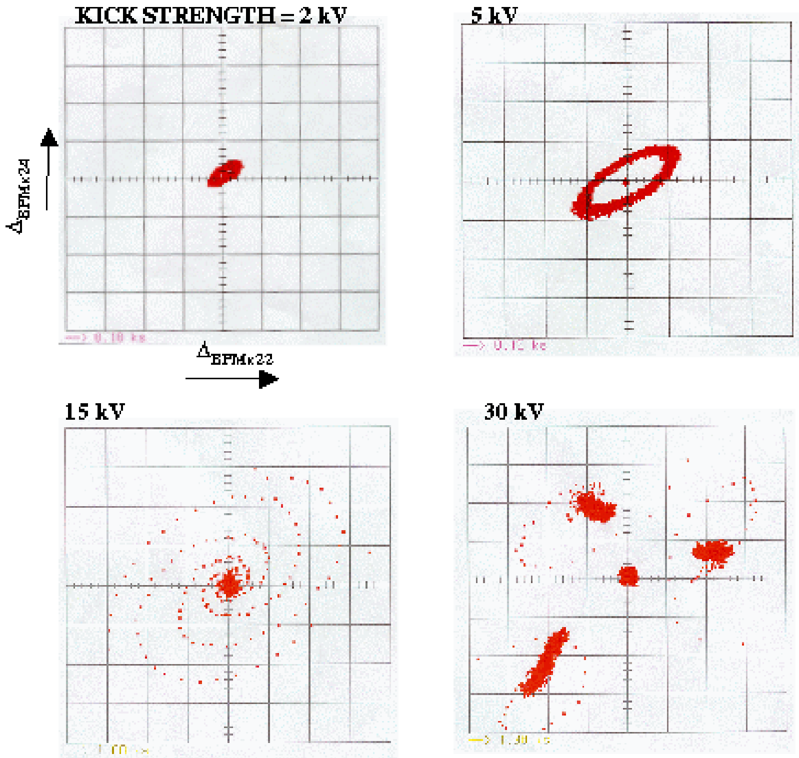

Figure 7. Horizontal ‘phase space’ plots of an electron-cooled beam at four different kick strengths in kV (deflection angles) displayed online with a digital storage oscilloscope in *xy*-display mode. Vertical direction: analog difference signal of BPM_{x24}, horizontal direction: analog difference signal of BPM_{x22}.

performs a circular motion around the center of the island, the so called stable fixed point. After about 37 turns the bunch returns to its original position in the island.

5. Ionization-residual gas ionization beam profile monitor

A profile monitor using a position sensitive micro-channel plate (MCP) detector [10] has been developed at the University of Bonn [11] and was tested and modified at FZ-Jülich [12]. A parallel ion drift field is maintained in the 130 mm wide gap between two electrodes. Residual gas ions are drifted onto an MCP assembly that provides a charge gain of about 10^7. The secondary charge produced from each ion is collected by a wedge and strip anode. The anode signal is then integrated by a capacitor, amplified and delayed for proper gating during the digitization. The read out is done by means of a PC running a user friendly Cobol PC program [10] under Windows OS.

Since COSY operates with beam intensities up to 10^{11} protons and a vacuum of 10^{-10} mbar, there is a big risk of radiation damage of the detector. Hence the MCP voltage is

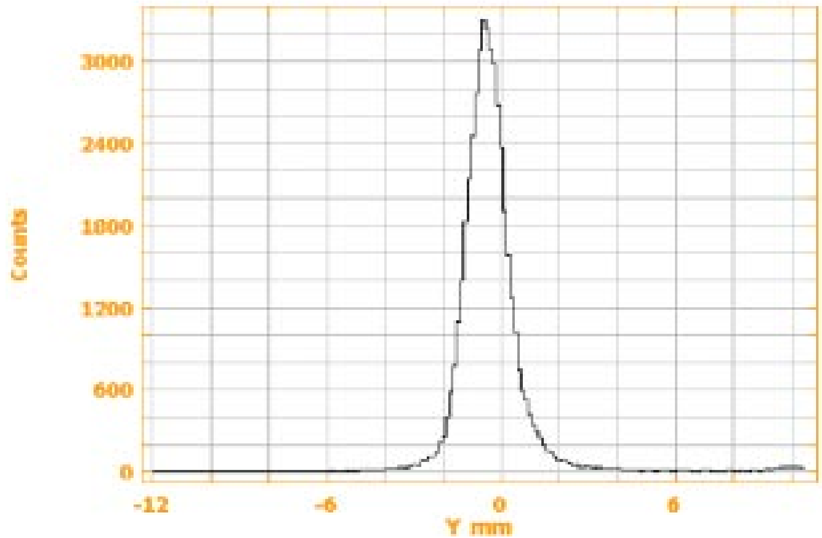

Figure 8. Vertical beam profile after electron cooling.

switched on only during the measurement (typically a few seconds). Also a pneumatically-driven protection screen is installed to prevent detector irradiation during the routine operation of the accelerator. Profile measurements have been carried out for beam intensities up to $2 \cdot 10^9$protons. Figure 8 shows the vertical beam profile after electron cooling for 6×10^7 protons at 40 MeV. The ionization beam profile monitor is used in routine operation. However, the comparison with two other methods shows that in case of cooled beam the profile is wider than the one measured by H^0 monitor (multi-wire proportional chamber), but if the beam was not cooled the profile is narrower than the one measured with EDDA wire target. This fact has not been properly understood yet. Monitor optics simulations show that potential distribution results in a slightly divergent effect on the residual gas ion trajectories. The optics of this monitor is under further investigation [13]. The life-time of the channel plates and the event rate are crucial issues for the measurement of intense proton beams.

6. New detector for spill measurements

The new detector for spill measurements is designed to measure with one compact device high resolution time structure and absolute intensity of extracted proton beams with energies above 50 MeV. The detector is suited for different type of extraction, from ultra-slow to kicker extraction, within an extremely wide intensity range from 0 to 10^{16}/s.

The device consists of two different detectors mounted in a steel pot of at least 92 mm inner diameter which in this case is connected to a CF100 cylinder via a bellow and can be moved pneumatically to and from the measurement position within <5 s. The detectors work at normal air condition which is a great advantage concerning costs and service especially with large UHV facilities. The wall of the steel pot is no real disadvantage as ultra-slow extracted beams have uniform intensity and cannot be detected with nondisturbing devices as beam position monitors or wall current monitors which need a pulsed beam. The thickness of the steel pot is 1 mm but can be made 0.1 mm around the sensitive area of the detectors. So even protons with energy below 50 MeV can be detected.

The first detector consists of two adjacent PMTs (photo multiplier tubes) each in variable light contact with a thin (2 to 5 mm) square shaped (65∗65 mm for CF63 beam tubes) plastic scintillator. Coincidence between the PMTs yields background-free absolute intensity in the range 0 to $5*10^6$/s. The variable light contact is performed by a switch selectable optical filter to reduce the light current to the PMTs by a factor of 10^4 to 10^6 to analyze the time structure of proton bursts from kicker extraction. In this case rates of 10^{16}/s may occur within 1 μs. Only the absolute intensity is then not available as the amplification of PMTs is normally unknown and not stable within an order of magnitude. The average anode current of one PMT reduced by its dark current is a measure of the proton rate if gamma background can be neglected. This measure is relative due to the unknown PMT amplification and average number of photoelectrons per proton but can be calibrated by the absolute intensity from the coincidence rate between 10^4/s and 10^6/s. The dark current must be measured within the extraction time of one cycle before the measurement cycle to take into account the gamma background as good as possible. The total influence of the gamma background, which should normally be negligible due to the small volume scintillators can be checked without beam. For rates above 10^8 the PMT amplification must be reduced by lowering the HV (high voltage) to stay below maximum anode current and within fair linearity. From dark current measurement as a function of HV the necessary HV reduction for 10 or 100 times lower amplification can be found. If the attenuation of the optical filter would be known, the particle number within a proton burst could be measured absolutely. This attenuation ($>10^5$) can be measured at stochastic extraction with high rates above 10^8/s by measuring the average anode current with and without optical filter.

The second detector is an ionization chamber mounted in the gap between the scintillators, followed by a current voltage converter with programmable gain for absolute intensity measurements of the higher rates from 10^4/s to 10^{10}/s and fair time resolution from dc to some hundred Hz. There is still a certain advantage if an additional ionization chamber is used. It is possible to compare its absolute extraction intensity with the values from the average anode current of the PMT above 10^5/s. Recombination losses due to the extremely high space charge up to 10^{12} ion pairs/cm^3 could be tested in an ionization chamber with the kicker extraction. Simultaneous measurement with a wall current monitor could also answer this question. A much more practical advantage of an ionization chamber is its use as a beam center and rough profile indicator if the electrode is divided into segments each with a separate electronic read out. In our case the electrode is divided in six segments (see figure 9).

7. Conclusions

The resonant tuning of the Schottky-pickup is now being tested in the machine. For tune measurements including the tune meter the Schottky-pickup is routinely used. The advantages of the tune meter include: (1) Spurious peaks with constant frequency can easily be recognized and separated. (2) No frequency feedback on the excitation is necessary.

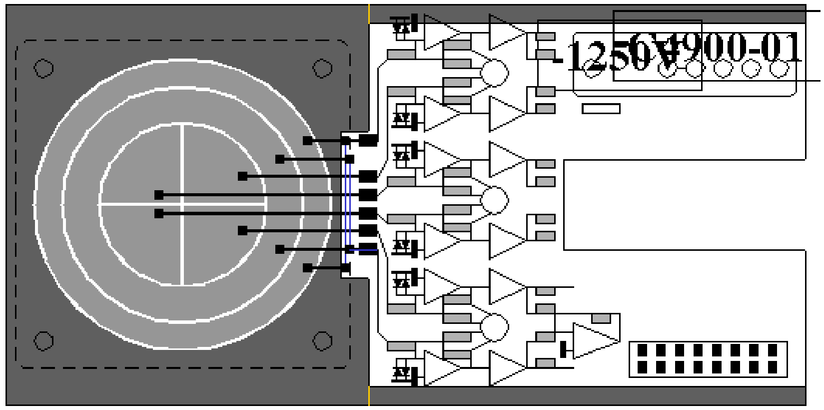

Figure 9. Six segment electrodes on a printed circuit board for the ionization chamber.

(3) The acquisition time is short, thus nonlinear changes of the tune have less influence on the accuracy. (4) Because of the bunch-synchronous sampling, all higher betatron side bands are transposed down and the FFT spectra contain only the frequency range up to $0.5 \times f_0$. (5) Due to the tracking clock, the longitudinal and transversal spectra are separated. (6) The gated low level excitation causes no noticeable particle losses. (7) The method with some additional signal conditioning can easily be implemented at multiple-bunch machines.

The studies of beam centroid motion after collectively perturbing the beam by a fast kicker yield important information about the lattice. This procedure is also useful in nonlinear beam dynamics studies. Due to the non-negligible beam size, the interpretation of the experimental results is difficult, especially if the beam center is displaced nearby the separatrix. Parts of the particles are stable here and the other parts are unstable. The degree to which the beam centroid motion accurately represents the motion of a single particle depends on the emittance of the beam; the smaller the emittance of the beam, the more accurate is its representation of single particle motion. Further limitations are the decoherence of the betatron motion and crossing of nonlinear resonances. The shown method is extremely useful to determine the transverse phase space online without analyzing the digitized FIFO memory of the beam position monitors.

The ionization beam profile monitor is used in routine operation. Some problems exist with the interpretation of the measured beam profiles, especially in the case of electron-cooled proton beams. The optics of this monitor is under further investigation. The lifetime of the channel plates and the event rate are crucial issues for the measurement of intense proton beams.

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