BUNCH SHAPE MEASUREMENTS AT INJECTOR 2 AND RING CYCLOTRON

R. Dölling, Paul Scherrer Institut, Villigen, Switzerland

Abstract

The longitudinal-horizontal 2-dimensional (2D) density distribution of a bunched 2.2 mA beam of ~72 MeV protons has been measured at the last turns of the Injector 2 cyclotron, in the middle of the transfer line to and at the first turns of the Ring cyclotron. Protons scattered by a thin carbon-fibre target are stopped in a scintillator-photomultiplier detector. The longitudinal bunch shape is given by the distribution of arrival times measured with respect to the 50 MHz reference signal from the acceleration cavities. More probes are foreseen at 72 and 590 MeV which will use additional fibres to also determine the longitudinal-vertical and two longitudinal-diagonal 2D density distributions. These measurements together with more detailed beam transport calculations will support the matching of beam core and halo and the quest for a reduction of beam losses. The achievable dynamic range in the given environment of the cyclotrons and the connecting beam line is discussed.

INTRODUCTION

The Injector 2 cyclotron delivers a 72 MeV 2.2 mA CW proton beam via a ~50 m long injection line to the Ring cyclotron, where it is accelerated to 590 MeV [1]. Beam loss is one of the main factors limiting the attainable beam current since hands-on maintenance is required for nearly all machine components. At this high current beam, already a thin beam halo contributes significantly to the beam losses. The transport of the whole distribution is strongly influenced by the beam space charge and the creation of new halo by scattering at collimators. Hence, already small changes at any location along the beam path can alter the total losses strongly. This makes setup and tuning difficult and leads to a tuning method mainly determined by examining the losses of the beam along its path and "turning all available knobs" to minimize losses at a given beam current level [2, 3]. Although this empirical concept is useful for finding the optimum operation for a *given* machine configuration, well-directed *changes* of the machine configuration, leading to significant improvement, cannot be initialized by it. Also it is very difficult to find hidden causes in the case of a persistently bad beam quality. To overcome this, detailed numerical simulations [4] of the beam transport and matching including the beam halo are required *together* with *detailed* measurements of the 6D phase space distribution. This should result in an improved beam cleaning at low energies by additional slits, a matched beam core *and* halo, lower losses at higher energies, the ability to setup the whole machine in one pass and the ability to find sources of deteriorated beam by examining the beam in detail.

The time-structure, i. e. the longitudinal bunch shape, is given by the distribution of arrival times of beam particles measured with respect to the 50 MHz reference signal from the acceleration cavities. In our case, protons are scattered by a thin carbon-fibre target towards a scintillator-photomultiplier detector [5, 6]. (This type of measurement is known since long and alternative methods are available [7-9].)

From the wire position also a transversal coordinate is determined. By moving the wire horizontally, a 2D profile of the bunch density "as seen from above" can be measured. This has been done at the last two turns of Injector 2, in the middle of the connecting line to the Ring cyclotron (approximately at the superbuncher position) and at the first two turns of the Ring cyclotron (Fig. 1).

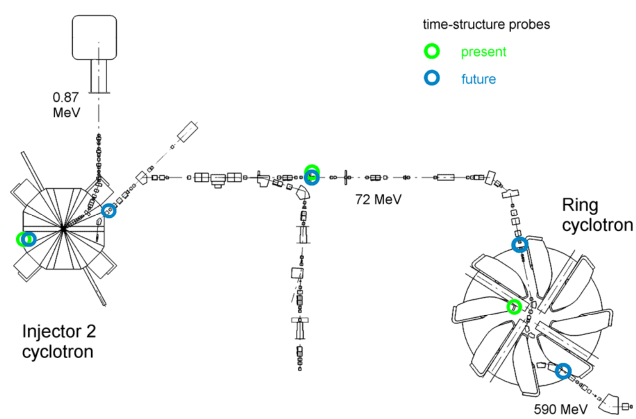

Figure 1: Locations of time-structure probes.

Repeating this with several wire orientations, does not yield the full 3D spatial charge density distribution, but rather several 2D projections. Hence, e.g. all 9 parameters describing size and orientation of an ellipsoid representing the bunch in real space can be determined and used in beam transport simulations on the matching of the beam core. More detailed information is available for detailed simulations including the beam halo. This type of measurement is under preparation for the last two turns of Injector 2, three locations in the connecting line and one behind the Ring cyclotron (Fig. 1).

The wire target precisely defines the location of measurement and hence the time-structure even of short bunches can be determined with good accuracy. Although the pulse width from scintillator and photomultiplier tube (PMT) is quite large (~3 ns fwhm), the time-resolution can be of the order of 30 ps due to the statistics from the many created photo-electrons [5]. However, the level of radiation background from beam losses strongly determines the achievable temporal and spatial resolution and the dynamic range.

EXPERIMENTAL SETUP

Due to the limited space in the cyclotrons, different arrangements of wire and detector are used at the three locations (Fig. 2). In any case the protons are scattered by 90°, travel a distance of ~0.3 m, pass a collimator and are stopped within the scintillator shortly before reaching the directly attached PMT. In the Ring cyclotron the placement of the detector in the median plane was unavoidable, thereby largely inhibiting a shielding by machine components and worsening the background from stray particles created by losses at other points in the cyclotron. The detectors are shielded with a few centimetres of lead, but especially in the Ring cyclotron with its high energy stray particles this is not effective.

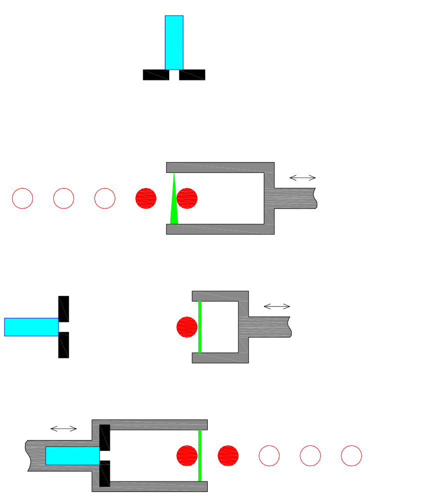

Figure 2: Setup at the three present locations (schematic; seen in beam direction). At Injector 2 the wire is tilted 45° in beam direction (the broader printed wire end is closer to the beholder).

The PMT pulses are transferred via long coaxial cables to the timing electronics outside the vault (Fig. 3). For time-structure measurement only a single PMT is selected together with the RF reference by switching the relays accordingly. For the location at Injector 2 the timing resolution can be determined from the coincidence between two detectors [5]. Time-to-amplitude converter (TAC) and multi-channel analyzer (MCA) are configured to divide 22500 ps to 512, 1024, 2048, 4096 or 8192 channels.

The horizontal stroke of the motorized vacuum feed-throughs is 100 mm. The time-structure is measured e. g. every mm with an accumulation time of 60 s. If a beam trip occurs, the measurement is paused until the difference to the initial beam current is below both 50 uA and 20%.

In case of the location in the middle of the connecting beam line, the changing path length from wire to detector is corrected for by shifting the individual MCA spectra in time accordingly.

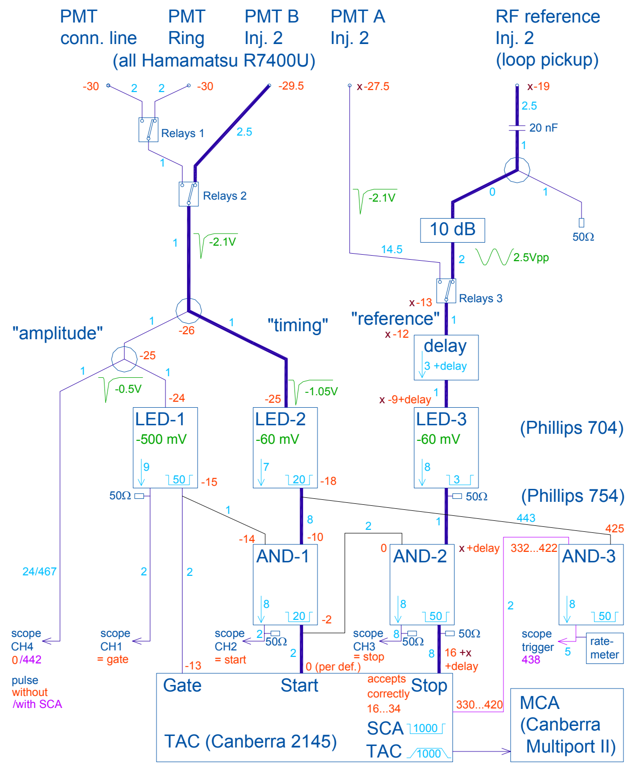

Figure 3: Timing electronics (relays are set for time-structure measurement at Inj. 2, timing path is printed thick). Signal and leading-edge discriminator (LED) levels are given in green, transfer times in ns in blue and time difference to "start" in ns in red. Components have been modernized compared to [5] giving roughly the same timing performance and allowing for an integration into the control system.

PULSE HEIGHT SELECTION

The highest pulses are expected from 72 MeV protons fully stopped in the scintillator. Their amplitudes at the leading-edge discriminator (LED 1) are adjusted to just above the discrimination level by adapting the supply voltages of the PMTs. Hence, pulses from low energy stray particles (as well as of protons of much higher energies) created from losses at other parts of the cyclotron, and protons from the wire which are degraded by grazing the collimator in front of the scintillator are largely suppressed (Fig. 4).

At Injector 2 a "static background" probably stems from losses at other places in the machine. There is also a signal component ("shadow bunch") always visible (Fig. 5), for which a conclusive interpretation is lacking. A description as beam particles of higher energy as suggested by the measurement is questionable. Those should arrive earlier, and the energy resolution of the detector seems to be too low to distinguish between protons of different turns. The similarity of the radial profiles of core bunch and "shadow bunch" hints to an artefact. However, no irregularities or relevant afterpulses of the PMT have been observed at the timing electronics.

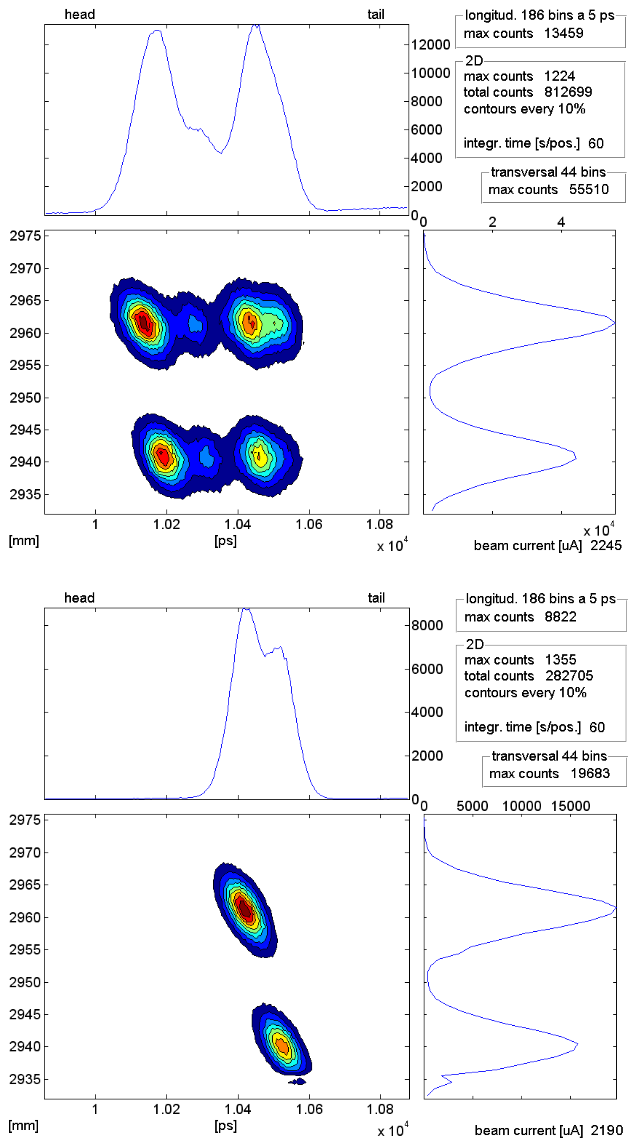

Figure 4: Time-structure measurement of the last two turns in the Injector 2 cyclotron (roughly 0.4 and 1.4 turns before leaving the cyclotron). Bunches as seen from above and projections. Upper part: Unsufficient suppression of the protons degraded at the detector entrance at a PMT voltage of 850 V (later 3 peaks, the collimator design is not optimal). Lower part: Better suppression at lower PMT voltage (800 V, time scale shifted due to changed relative trigger level). The core bunches are nearly round (10 mm correspond to 90 ps; the dip at 2935 mm is due to a malfunction of the measurement software). The bunch centers lie on a radius to the machine center.

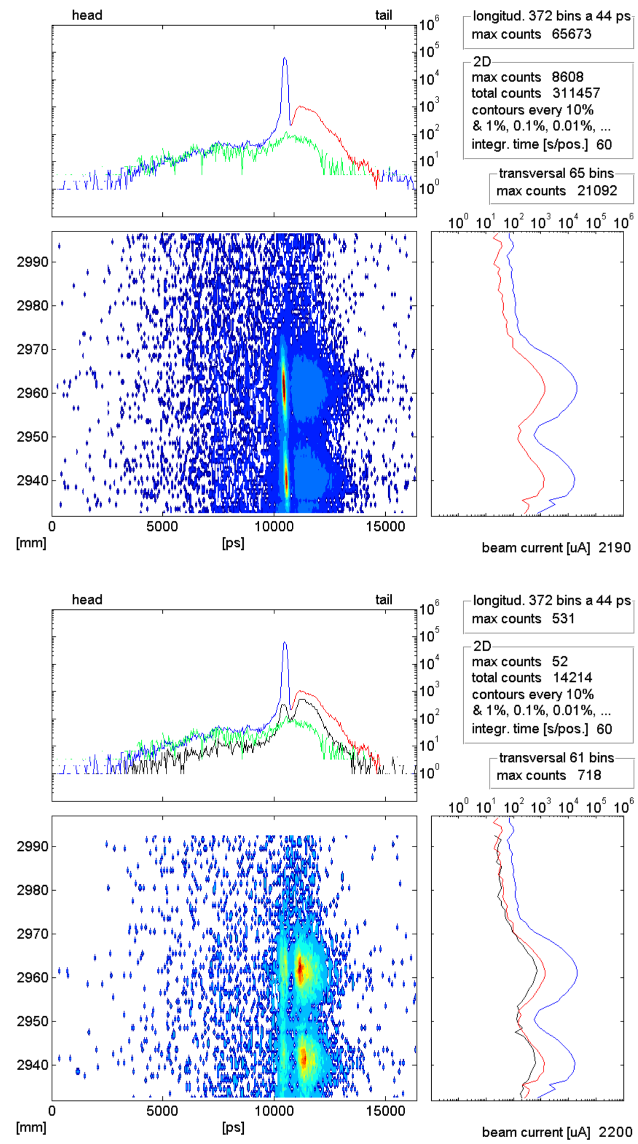

Figure 5: Upper part: Same data as Fig. 4 lower part, but resampled to larger time bins (single event bins are visible; the 10%-level is given by the border between cyan and light blue). A time dependent but position-independent broad "static background" is best visible at radii above 2980 mm (green curve in the projection derived from that radial range and adapted in height). The longer "shadow bunches" marked in red in the time projection have a radial profile (red) similar to that of the full projection (blue) and hence similar to that of the core bunches. They correspond to 1/12 of the beam current. Lower part: With further decreased PMT voltage (780 V). Projections are black (colored projections copied from upper part to indicate the difference). The "Static background" and the long "shadow bunches" have decreased, but much less than the core bunches. The "shadow bunches" now account for 77% of the signal.

DYNAMIC RANGE

At Injector 2 the dynamic range can possibly be improved by better shielding of the detector. However it is mainly determined by the interpretation of the "shadow bunch".

In the "quiet" environment of the connecting beam line a "static background" is completely missing (Fig. 6, upper part). At moderate PMT voltages the dynamic range is determined by the counting statistics. With a larger bin size a value of 10^5 is achievable for the projected profile.

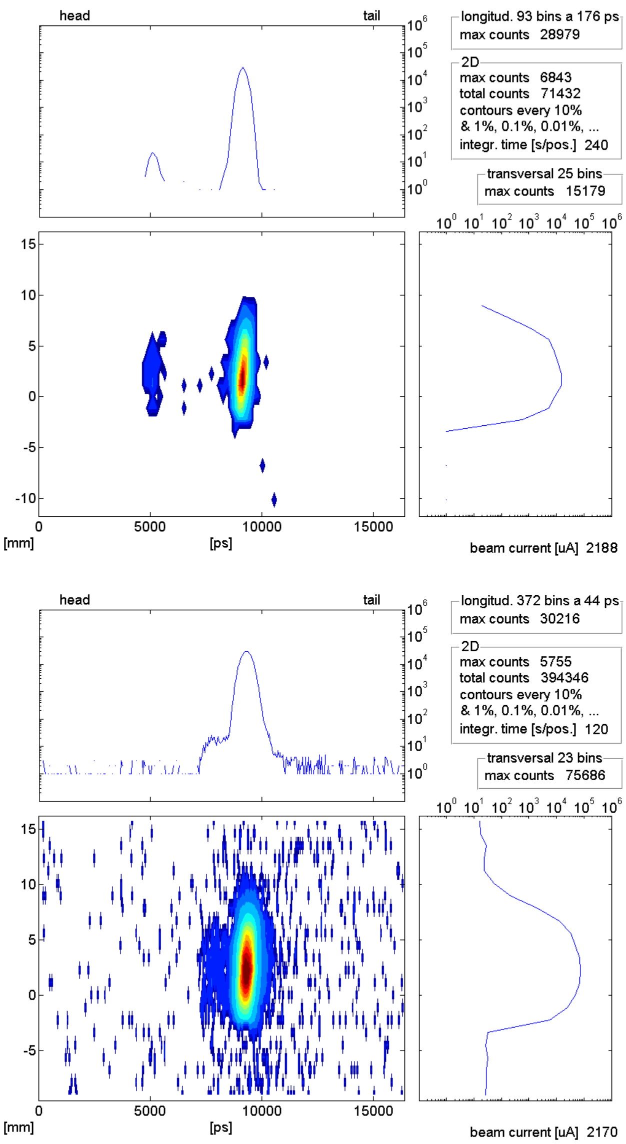

Figure 6: Time-structure measurements in the connecting beam line. The bunch is cut sharply at its left side due to the upstream electrostatic septum, peeling off ~60 µA to the material irradiation area. The "shadow bunch" visible at a level of 10^{-3} is identified as an artefact from reflections in the timing electronics because it shifts relative to the core bunch when internal cable lengths are changed. Upper part: Moderate PMT voltage (720 V). Lower part: Too high PMT voltage (750 V).

At the Ring cyclotron the dynamic range is limited by the high background level due to the energetic stray particles. For a projected profile it is of the order of 10 as can be seen from Fig. 7. With even longer accumulation times, enlarged bin width and somewhat lower beam losses a value of 100 might be possible.

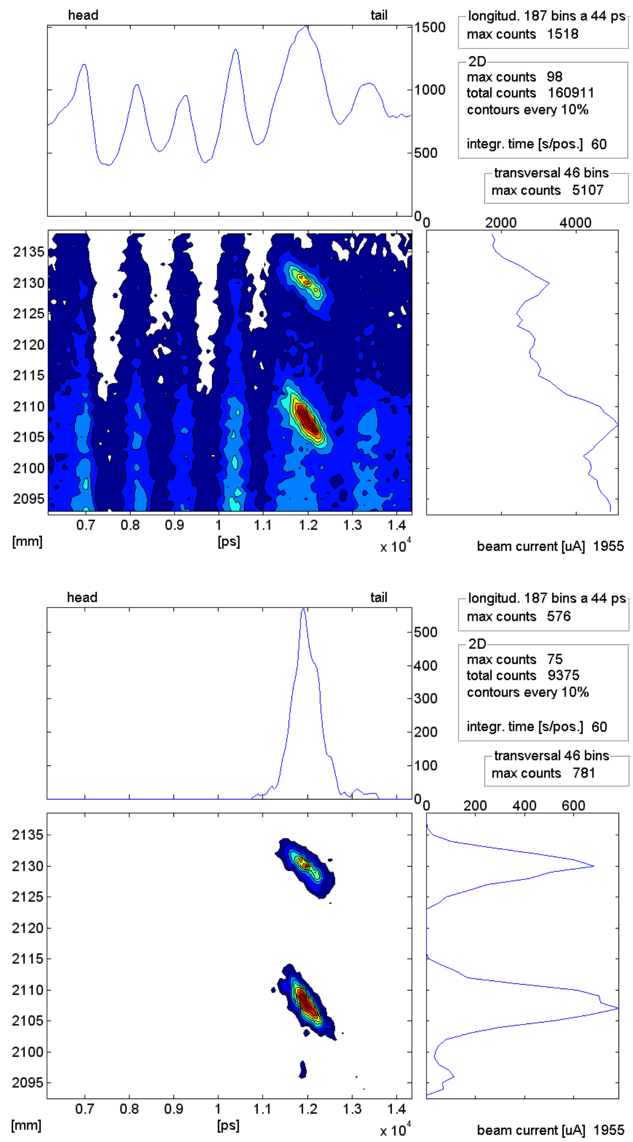

Figure 7: Time-structure measurement of the first two turns in the Ring cyclotron (after completing 0.6 and 1.6 turns) at relatively high beam losses. Without and with background subtraction and filtering (see text).

BACKGROUND SUBTRACTION

The following steps are only performed at the Ring cyclotron in order to cope with the background signal: Artefacts from out-of-range late "stop"-events are eliminated. The MCA spectrum at each probe position is smoothed by applying two times the 25%/50%/25% averaging algorithm. The background is subtracted in the following way: The time-structure of the background is assumed to be constant for all wire positions. The background amplitude is assumed to change linearly from the initial value with the wire at a lower machine radius to the end-value at a higher machine radius (due to the co-movement of the detector in the background radiation of the cyclotron). The time-structure of the background is determined from the average (projection) of the MCA spectra at the three smallest and three largest machine radii. (The radial range of measurement must be chosen in a way that these points are between the turns and outside the last turn and hence are nearly not affected by beam signal.) The background amplitude at the second lowest radius is determined from the average (sum) of the MCA spectra at the three lowest radii; and similarly at the second highest radius. After subtracting the so-defined 2D background from the 2D signal, a further 2D filtering is applied to remove "islands" formed due to statistical noise: Only those bins are valid which have >30% of the counts of the maximum bin *or* have >3% *and* are connected via a chain of neighbour bins (in time or radius) of >3% to a bin of >30%. All others are set to zero. The effect of this procedure is shown in Fig. 7.

FOUR 2D PROJECTIONS

One of several possible configurations allowing for the measurement of four 2D projections of the bunch density using a single detector and two motorized feedthroughs is depicted in Fig. 8. It will be used at all beam-line locations. The detector is placed below the beam line and, more important, below the center plane of the cyclotron where some shielding is provided by the magnets. The secondary emission currents from the 33 µm carbon fibres will be read out in addition, allowing for fast transversal profile measurements. Signals from both wire ends are connected to the outside to allow a check of wire integrity.

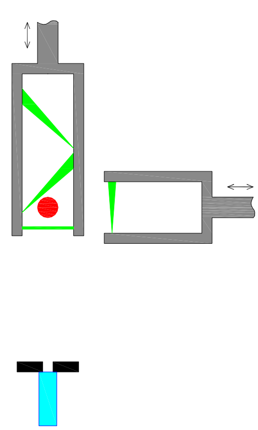

Figure 8: Orientation of wires, drives and detector for a measurement of four 2D projections in the beam lines (schematic; seen in beam direction). Most wires are tilted 45° in beam direction (the broader printed wire ends are closer to the beholder). Wire centers and scintillator axis are in one plane transversal to the beam.

The fast plastic scintillator will be directly attached to a double anode PMT to allow for a verification of the time resolution, similar to [5]. Signals from both anodes are either separately fed to the timing electronics or combined by a relays directly at the PMT to give the full photo-electron statistics during normal operation. The entrance aperture to the scintillator will be somewhat larger to increase the count rate to shorten the rather long measurement duration.

CONCLUSION

The dynamic range of the time-structure measurement in the Ring cyclotron is much lower than at the other locations. Nevertheless, the ensemble of measurement devices can deliver information on the bunch shape which is valuable for the understanding of the matching of beam core *and* halo between Injector 2 and Ring cyclotron and of the beam transport in the cyclotrons. It will be used more extensively in the future.

ACKNOWLEDGEMENTS

The Author would like to thank T. Korhonen for the implementation of the measurement routines and timing electronics into the control system.

REFERENCES

[1] M. Seidel et al., "Production of a 1.3 MW Proton Beam at PSI", IPAC10, p. 1309.
[2] T. Stammbach, "Experience with the High Current Operation of the PSI Cyclotron Facility", CYC92, p. 28.
[3] R. Dölling, "Beam Diagnostics for Cyclotrons", CYC10.
[4] Y.J. Bi et al., "Towards Quantitative Predictions of High Power Cyclotrons", CYC10.
[5] R. Dölling, "Measurement of the Time-Structure of the 72-MeV Proton Beam in the PSI Injector-2 Cyclotron", DIPAC01, p. 111.
[6] R. Dölling, "New Time-Structure Probes between Injector and Ring Cyclotron", PSI Annual Scientific Report 2004, Vol. VI, p. 15.
[7] W.R. Rawnsley et al., "The Production and Measurement of 150 ps Beam Pulses from the TRIUMF Cyclotron", CYC84, p. 237.
[8] T. Milosic et al., "Longitudinal Emittance Measurement Using Particle Detectors", DIPAC09, p. 330.
[9] E. Griesmayer et al., "Diamond Detectors as Beam Monitors", BIW10.
[10] K. Wittenburg, "Halo and Bunch Purity Monitoring", CAS2008, http://cas.web.cern.ch.