BEAM INTENSITY MODULATION AT THE PSI PHILIPS CYCLOTRON

P.A. Schmelzbach and Th. Stammbach for the Injector 1 Crew
PSI, CH-5232 Villigen PSI, Switzerland

Abstract

The intensity delivered by the PSI Philips Cyclotron is controlled by means of an electrostatic deflector and collimators located close to the center of the accelerator. This system allows for the precise stabilization and smooth modulation of the beam intensity, the generation of beam pulses of variable length and repetition rate, and the fast interruption of the beam in case of emergency. This technique is particularly well suited for present and future medical applications.

1 INTRODUCTION

The PSI Philips Cyclotron, locally known as Injector 1 because of its previous use as injector for the PSI Ringcyclotron, is a very versatile machine having accelerated proton beams of up to 200 µA at 72 MeV in the injection mode (50.6 MHz RF). It is now employed for the production of protons, deuterons, alpha-particles and lighter heavy ions in the variable energy mode (4.5 to 17 MHz RF). One important use of the accelerator is the production of 72 MeV protons for the eye cancer treatment program OPTIS.

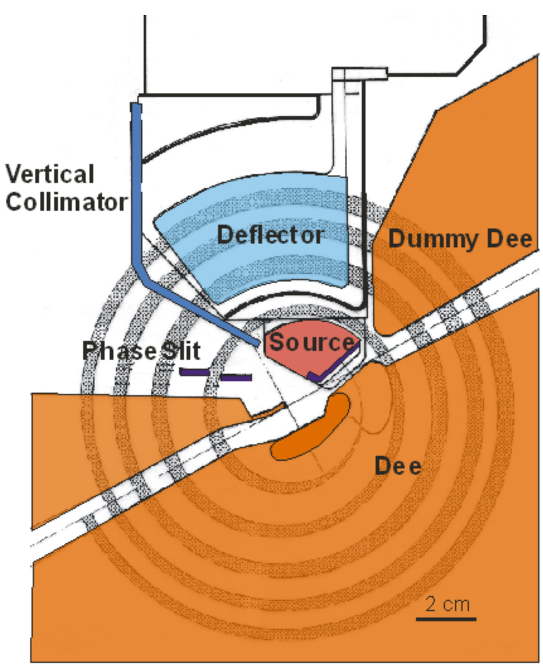

Figure 1: The center region of the PSI Philips Cyclotron.

An important feature of this cyclotron is the special design of the beam collimation in the center region in order to achieve a high beam quality, allowing for the requested excellent extraction efficiency in the injector mode. This approach might be of interest for the design of cyclotrons supposed to fulfil high requirements in respect of radioprotection standards, especially regarding the minimization of component activation.

Another interesting aspect is the control of the beam intensity. A deflector bending the beam vertically in front of the collimator is very successfully used for this purpose. The advantages of this technique are evident: it relies on a control parameter dedicated solely to this function, the ion source can be permanently operated in its most stable mode, the dynamical range is very large and reproducible, and a fast control is easily achievable. Contrary to the results obtained with RF-amplitude modulation, a smooth behaviour of the intensity variation and constant optical properties of the extracted beam have been demonstrated. The danger that the beam can pass outside the phase slit is excluded.

The vertical deflector can indeed also be used as a beam switch. This permits running the source and RF system between irradiation periods, thus eliminating instabilities due to warm-up effects as production restarts.

A sketch of the center region with the innermost turns is shown in Fig. 1. The PIG ion source, the 5 mm thick vertical copper collimator and the deflector are mounted on a common frame movable in all three coordinates. An adjustable phase slit in the first turn provides, in combination with the exit opening of the ion source, some radial collimation. The Dee voltage is about 70 kV in the 50 MHz mode. In the variable energy mode, voltages between 20 and 50 kV are used.

2 VERTICAL COLLIMATION

The function of the vertical collimator has been described in some detail in ref. [1] and only a few features are repeated here. The collimator has an aperture of 7 mm. After 10 turns, the transmitted part of the beam matches the eigenellipse of the vertical motion in the cyclotron. The shadowing effect of subsequent passes through the collimator is illustrated in Fig. 2.

The selected part of the beam can be accelerated and extracted without major losses, as shown in Table 1. Since the septum itself intercepts 7 % of the beam, a figure of 91 % for the extraction efficiency, defined as the ratio of the extracted current to the one measured at a radius of

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90 cm (the beam is extracted at 104 cm), demonstrates that the vertical collimation of the beam in the machine center is a key element in the design of a clean accelerator.

Table 1: Beam transmission vs. vertical collimation

Vertical collimation	Transmission			
	20-60 cm	20-90 cm	20-extr.	**90-extr.**
none	100 %	82 %	58 %	**71 %**
1 turn	100 %	93 %	66 %	**71 %**
10 turns	100 %	93 %	85 %	**91 %**

Especially at high beam curents when the source is operated at saturation, the initial beam has a large divergence and only a small fraction is transmitted, i.e. the collimator defines a new origin and decouples the optical properties of the beam from the conditions upstream of its position. Furthermore, using only the core of the beam has the advantage of diminishing the influence of the fast instabilities arising from the plasma oscillations in the ion source.

Due to the phase dependence of the vertical oscillations, the collimator is also used as a phase selector by inducing a collective oscillation in the center by moving the ion source vertically out of the plane of symmetry. This method works also at high beam intensities, whereas the large beam divergence makes the phase selection by the phase slit rather ineffective.

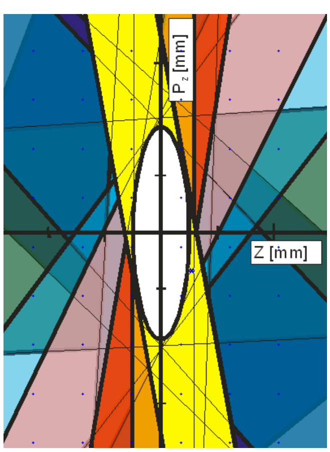

Figure 2: Matching of the beam phase space to the eigenellipse of the vertical motion in the accelerator by means of multiple passes through the vertical collimator.

3 THE VERTICAL DEFLECTOR

The vertical deflector consists of two electrodes 15 mm apart generating a vertical electric field acting on the 2nd to 4th turns as shown in fig. 1. The deflector is protected from the beam by the vertical collimator in front of it and a surrounding housing reduces the RF pick-up. The latter is a very critical point which is taken into account by overrating and cooling the electrical conductors located inside the hollow rods supporting the source body.

The beam deflection results in a change of the illumination of the phase space defined by the vertical collimator. Therefore, a pure beam intensity modulation can be achieved with this system, letting the optical properties of the beam be independent of its intensity.

In the standard configuration, a voltage between –2 kV and +2 kV is applied to the lower electrode. The application of a voltage of 3 kV to the upper electrode allows for fast suppression of the beam. This function is used to switch off the beam at the end of an irradiation when the planned dose is reached or during the time a beam stopper is moved in or out of the beam.

4 BEAM INTENSITY MODULATION

A typical behaviour of the beam intensity as a function of the voltage applied to the deflector is illustrated in Fig. 3. The smooth dependence, together with the use of a high resolution DAC, allows for a precise control of the beam intensity by means of a close-loop feedback system fed by the signal delivered by current monitors such as the pick-up detector at the exit of the cyclotron or the current integrators of the beam dumps in the experimental areas. For the OPTIS application, the output of an ionization chamber located near the scattering foil is used.

Since the vertical collimator decouples intensity and beam optics, variations of the latter can be tracked back to other drifts which are mainly due to instabilities of the magnetic field. Therefore, changes in the phase and the position of the extracted beam, detected by the pick-up detector or by a pair of slits, can be used as input in the phase control loop tuning the magnetic field.

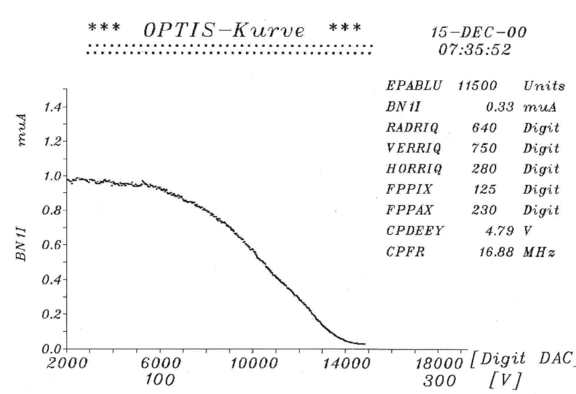

Figure 3: Beam intensity as a function of the deflecting voltage. For the OPTIS application, the ion source position and the phase slit are positioned such that the beam intensity cannot exceed 1 μA.

This simultaneous, uncorrelated control of the beam characteristics is essential for experiments where geometry and timing are crucial parameters

While its main purpose is the stabilization of the dc beam current, the vertical deflector is also well suited for the production of beam pulses of various lengths and repetition rates. Since macropulses with repetition rates in the kHz range can be of practical interest in a variety of applications, the properties of such pulses with a nominal length of 500 ns at a repetition rate of 1 kHz will be discussed in the following. The tests have been performed with a 80 µA, 72 MeV proton beam accelerated in the variable energy mode (17 MHz). The pulsed beam intensity was 45 nA.

The 1 kV pulsed voltage is applied to the lower deflector plate and a dc bias with the reverse polarity is adjusted in order to reach the desired suppression factor between the beam pulses. Both signals are fed by a mixing circuitry to the lower electrode since the upper one is always reserved for the fast beam switch-off function

The amplitude of the signal from the beam pick-up detector is shown in Fig. 4. As seen in the figure, a very good separation can be achieved. With bias voltages over 1500 V, a suppression ratio of several orders of magnitude is reached, however at some cost of the beam intensity. The working point at which the pulse properties were investigated is also indicated.

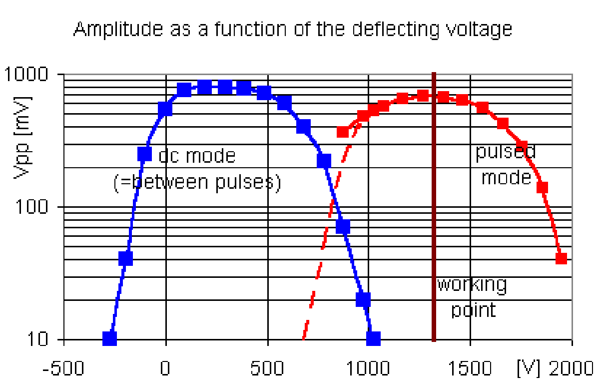

Figure 4: Amplitude of the macropulse as a function of the bias voltage added to the 1 kV pulse applied on the deflector.

The shape of the beam pulse depends on the rise time of the deflector voltage and on the tuning of the cyclotron. Four examples are shown in Fig. 5 to demonstrate the influence of small variations of the magnetic field. The rise time of the deflector voltage is 100 ns. For a well tuned beam, the FWHM of the beam pulse is 650 ns, the raise and fall-off times are 350 to 400 ns and the delay due to the time of flight through the accelerator amounts to about 8 µs. The pulse shape and the flight time are clearly sensitive to the fine tuning of the magnetic field. The setting of the phase slit is also important.

The present investigation shows that, under standard conditions, beam macropulses with a FWHM below 2 µs can easily be produced. A test at a repetition rate of 400 kHz showed that well separated pulses can be obtained, even if at this duty factor, the voltage delivered by the power supply to the deflector has a rise time of 200 ns and an amplitude of only 600 V.

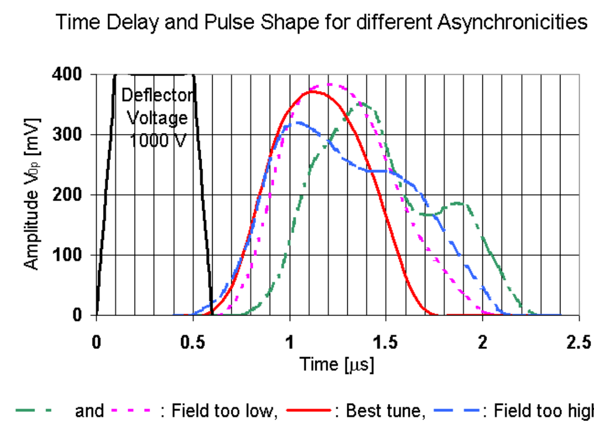

Figure 5: Time structure of a beam pulse generated by a 1 kV, 500 ns long pulse applied to the deflector. For the beam pulses the horizontal scale is shifted by 7 µs

Finally, a very special application of the vertical deflector should be mentioned. Using an appropriate high power amplifier, it was possible to achieve a clean 1 to 3 single pulse selection in the 50 MHz mode of operation.

4 CONCLUSION

The vertical phase space selection by means of a collimator intercepting many beam turns close to the center of the cyclotron makes it possible to use a vertical deflector to control the intensity of the beam with a high accuracy, and without affecting its optical properties. This method is well established at the PSI Philips Cyclotron and has proven its ability to satisfy the highest requirements set on the extraction efficiency and on the dynamical range of the beam intensity modulation. The smooth dependence as a function of the voltage applied to the deflector allows for a fail proof control of the beam intensity as needed for medical applications. The generation of macropulse with repetition rates up to several hundreds kHz is easily achieved.

REFERENCES

[1] G. Heidenreich and Th. Stammbach, “Some Aspects of the 100 µA Operation of the SIN Injector Cyclotron”, 9th Int. Conf. On Cyclotrons and their Applications, Caen, 1981.