TRACES OF THE VORTEX EFFECT IN PSI INJECTOR II

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Abstract

Injector II is part of PSI's high intensity proton accelerator (HIPA) facility. It is to date the only cyclotron worldwide that makes use of a space-charge driven effect ("Vortex Effect") which causes bunches not to expand but to "roll up" in the horizontal plane. The effect prevents the cyclotron bunches from expanding longitudinally so that the phase width stays unusually small and the former flat-top resonators could be replaced by normal accelerating resonators. The effect has been simulated in PIC-codes like OPAL and experimentally verified by bunch shape measurements. We present measurements of radial probes which contain residual traces of this effect and we show how it is used to analyze and fit the beam optics in the transfer line between Injector II and the Ring cyclotron.

THE HIGH INTENSITY PROTON ACCELERATOR (HIPA)

The accelerator part of the high intensity proton accelerator facility (HIPA) [1] is shown in Fig. 1. The DC proton beam is generated by an ECR ion source and accelerated by a Cockcroft-Walton to 870 keV. Two bunchers, a first and a third harmonic, enhance the proton density within the phase acceptance of the Injector II cyclotron. After extraction at 72 MeV the beam is guided in the IW2-beamline to the injection of PSI's Ring cyclotron. The Ring cyclotron accelerates the bunches to 590 MeV before two sequential graphite targets are used to generate pions and muons. The re-collimated beam is then transported to the Swiss spallation neutron source SINQ (not shown). If the space charge

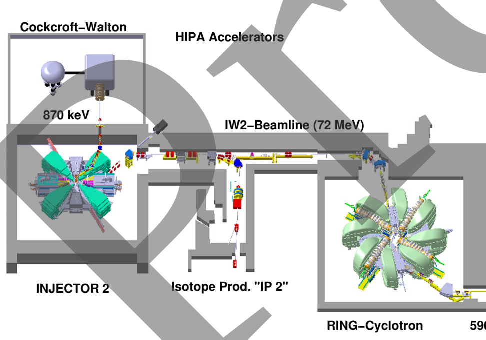

Figure 1: Layout of PSI's High Intensity Proton Accelerators (HIPA). The experimental areas and user facilities are not shown.

self-force of bunches in isochronous cyclotrons is strong enough, then it induces the so-called "Vortex effect", first described by Gordon [2]. The effect can be attributed to the coupling terms between the longitudinal and the transverse-horizontal beam motion [3, 4]. The Vortex effect leads to the formation of almost round bunches with dense cores. Depending on the details of the bunch formation halos in the form of tails or side-bunches are formed, typically in two opposite arms [5]. The Vortex effect prevents bunches from expanding longitudinally which leads to an unusual short phase width. This allows to operate the former flat-topping resonators (third harmonic, 150 MHz) in accelerating phase, thus reducing the number of turns from about 100 [6] to about 83. Furthermore it suggested to upgrade Injector 2 and to replace the low-voltage former flat-tops by high-voltage accelerating resonators operating at the first harmonic of 50 MHz [7]. The upgrade project has been completed, with some delay, in 2025 and enabled to further reduce the number of turns from about 83 to now about 60. This decreased the losses in the Ring cyclotron in 2025 by a factor of 4 compared to 2015.

INJECTOR II: BUNCH CORE

The bunch core can be described by the theory of linear coupled optics. The non-linearity of the space-charge force outside the bunch core leads to self-matching by filamentation and emittance increase. Then the linear theory allows to determine the parameters of matched bunches, provided beam current and emittances are known [4, 8–11]. Figure 2

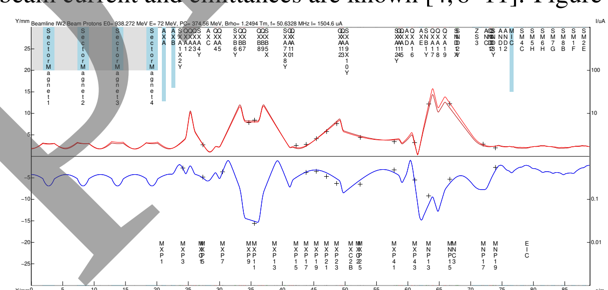

Figure 2: Fitted beam envelopes [10] ("x" in blue, "y" in red) from the last turn of Injector II along the transfer line "IW2", including the first turn of the Ring cyclotron. The crosses indicate the beam size ($2\,\sigma$) as measured by beam profile monitors.

shows a fit of the optics of the beam transfer line based on a matched beam in the last turn of Injector 2, varying only the (eigenvalue-) emittances. A series of these fits for various beam currents allows to obtain the emittance in dependence of beam current (Fig. 3) and to confirm theoretical calculations which suggest that [4]

$$\sigma^4 - K\,I\,\sigma - \frac{4\,\varepsilon^2\,R^2}{\gamma^2} = 0\,, \tag{1}$$

where σ is the radius of the (spherical) bunch, ε the (horizontal) emittance, R the radius in the cyclotron and K a perveance:

$$K = \frac{R^2\,q}{5\,\sqrt{5}\,\pi\,\varepsilon_0 f_{rf} m\,c^2\,\beta^2\,\gamma^4}\,. \tag{2}$$

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If the maximal current is proportional to the square of the

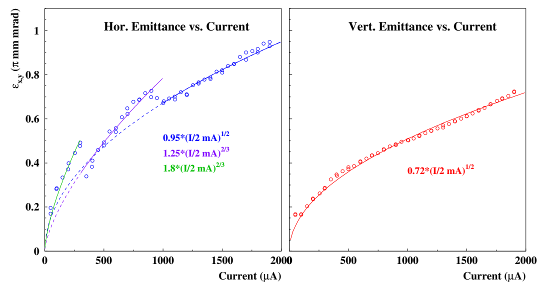

Figure 3: Fitted (eigenvalue-) emittances versus beam current. The horizontal emittance is shown on the left (with traces of current-dependent collimation) and the vertical on the right.

emittance $I \approx C\,\varepsilon^2$ (Fig. 3), then one obtains

$$I = \frac{\sigma^4}{(K\,\sigma + \frac{4\,R^2}{C\,\gamma^2})}\,, \tag{3}$$

in agreement with measurements and simulations, which indicated $I \propto \sigma^k\;\; k \in [3\ldots4]$ [12]. The adjustable colli-

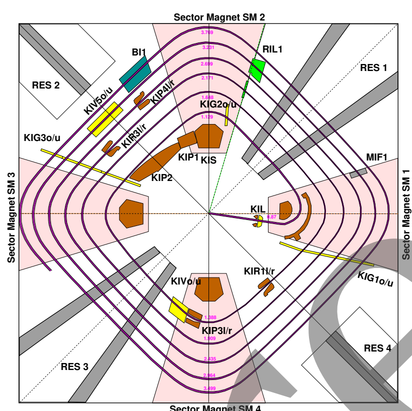

Figure 4: The first few turns within Injector II with various radial and vertical collimators, most of which are adjustable.

mators of Injector II as shown in Fig. 4 are used to remove (part of) the halo which allows to extract the beam with low losses [11, 12].

INJECTOR II: HALO MOTION

If the orientation of the halo tails at a radial collimator is transverse to the beam direction, the halo wings are removed (see Fig. 5). The relative orientation of the tails depends

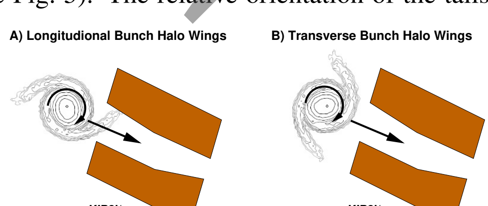

Figure 5: The efficiency of halo removal depends on the orientation, which depends on beam current.

on the details of the injected beam distribution, the bunch formation and on the beam current. Hence ramping up the beam current makes the halo rotate around the core which generates maxima and minima in the extraction losses, as shown in Fig. 6. These can be measured by the ionization

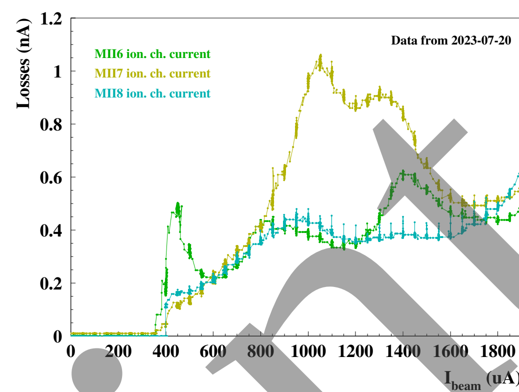

Figure 6: Losses measured by the ionization chambers MII6, MII7 and MII8 versus beam current.

chambers MII6, MII7 and MII8 (see Fig 7) which are located behind the electrostatic deflector EID and the septum magnet AXA. Direct experimental verification of the round bunch shape has been obtained by so-called *bunch shape measurements* [13–15]. However bunch shape measurements are time consuming and have a limited resolution and signal-to-noise-ratio. But also the radial beam profiles measured by the short radial probes RIE1 and RIE2 can provide information about the location of halo tails (Fig. 8). The tune Q_h of

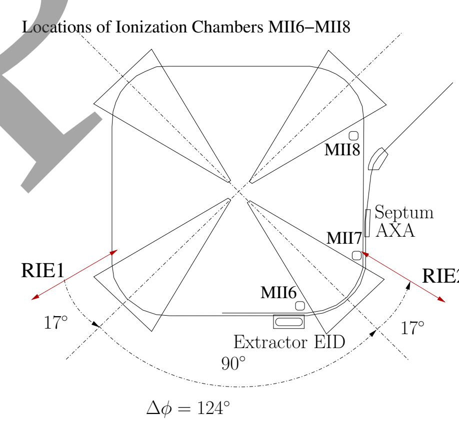

Figure 7: Locations of ionization chamber MII6, MII7, MII8 and radial probes RIE1 and RIE2 of Injector II.

the halo motion around the bunch can be approximated by:

$$Q_h = -Q_r + C\,\frac{E_r(r)}{Q_r\,r}\,, \tag{4}$$

where r is the distance to the bunch core and $E_r(r)$ the electric field. If a halo peak has a radius large enough to be distinguishable from the core, then the electric field is weak enough to assume that the tune corresponds to the radial tune Q_r, which is approximately 1.3. Then the halo position relative to the core should repeat after $\approx$ 3 turns - in

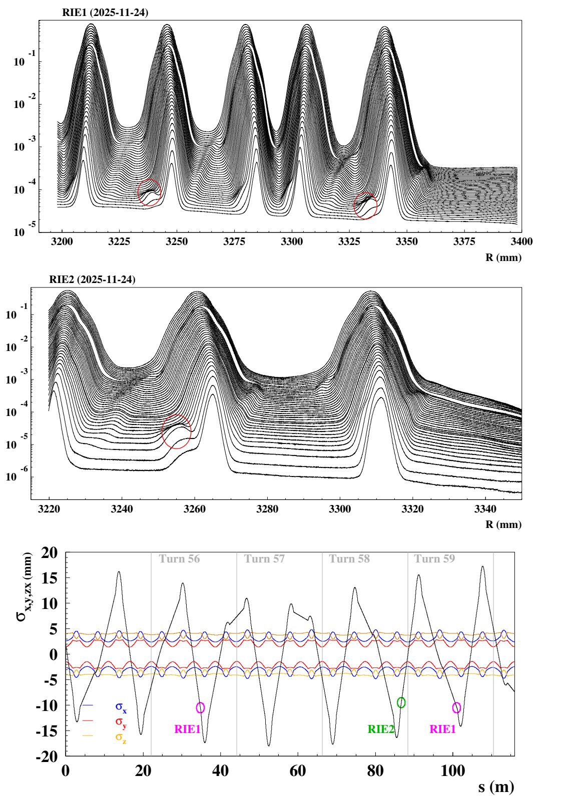

Figure 8: Top: Logarithmic plot of RIE1-scans for various currents, increasing from red to blue. At low currents the halo is clearly visible and the pattern repeats (as expected) after 3 turns. Middle: Same measurements with RIE2. The second-last turn shows the same halo shape as visible with RIE1. Since the angular distance is 124° (or 236°, respectively) and the tune $Q_r \approx 1.3$, the halo reappears one turn later in RIE1. The curves have been schifted vertically for better visibility. Bottom: The indicated halo positions agree well with the space-charge-free betatron motion.

good agreement with the measurements shown in Fig. 8. As the Vortex effect forms a metastable state which is sensitive to various distortions [16], the size and position of the halo peaks relative to the bunch depends on various parameters like buncher voltage and phase, quadrupole and steerer settings in the injection beam line, trim-coil currents and collimator positions in Injector II and resonator ("Dee") voltages. Hence the yearly setup of the machine may take several shifts of beam tuning and requires well-trained and experienced operators to minimize halo formation and losses. This holds specifically after big changes like the installation of new resonators. However, once the facility is tuned it operates with low losses and high reliability and provides the most powerful proton beam of all cyclotron facilities world-wide.

SUMMARY AND CONCLUSION

The former flat-top resonators of the Injector II cyclotron at PSI's HIPA facility have been replaced by first harmonic resonators. This reduced the turn number from formerly 83 to 59 and, due to increased turn separation, the losses to an all-time minimum. The beam dynamics of the bunch core of Injector II, which is dominated by the space-charge induced "Vortex effect", is well understood in linear approximation and well-confirmed by simulation and measurement. The bunch (and halo) formation and the motion of the halo however depends on many parameters and is highly nonlinear. A careful setup and tuning of the machine by experienced operators is required.

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