THE COMMISSIONING OF PSI INJECTOR 2 FOR HIGH INTENSITY, HIGH QUALITY BEAMS

J. Stetson,
National Superconducting Cyclotron Laboratory,
East Lansing, MI 48823, USA

and

S. Adam, M. Humbel, W. Joho, Th. Stammbach,
Paul Scherrer Institute (PSI),
5232 Villigen, Switzerland

ABSTRACT

Since 1984 injector 2 is producing beams of 72 MeV protons for injection into the 590 MeV ring cyclotron of PSI. The RF-system of this ring is not yet able to accelerate beams above 0.6 mA, but the injector 2 has been commissioned to produce beams with intensities of up to 1.5 mA. Theoretical investigations done in parallel with beam experiments have helped to increase maximum extracted beam intensities and, to simultaneously improve beam quality at these higher currents. Simulations of bunching effects under space charge conditions predicted a high intensity kernel in the injected beam with minimal energy spread. Studies of the phase selection mechanism in the cyclotron center aimed at selecting this beam part for acceleration. As a result of these studies, an additional phase cutting collimator was installed, the buncher voltage was increased and its phase was stabilized.

1. LAYOUT

The following discussion principally concerns the PSI 72 MeV injector 2 and associated 870 keV proton injection beam line.

The acceleration process begins with protons extracted at 60 kV from a multi-cusp type ion source. This first beam is focused into the 810 keV acceleration tube of the Cockroft Walton DC accelerator. The 870 keV beam line, located on a level of 3 meters above the cyclotron midplane, leads the protons towards the cyclotron center. Two 90 degree bending magnets guide the beam vertically down and back horizontally into the midplane of injector 2. An Alvarez-type buncher is located near the end of the horizontal section, shortly before the downward bend. Injection, acceleration and phase selection of the 870 keV beam in the center region is shown in fig. 1.

Acceleration in the cyclotron is done by two 50 Mhz delta-shaped (two-gap) resonators with a voltage per gap that rises radially from 125 to 250 kV. Flattopping over about ±20 RF degrees is achieved by two third-harmonic (one gap) cavities beginning on the fifth orbit. Extraction at a radius of 3 meters occurs after ≈102 turns. The limits of extracted beam current are set in an absolute sense by the losses allowable in the extraction system (a total of about 3 μA) and by the goal of having beam of sufficient quality for transmission and acceleration in the 590 MeV ring cyclotron.

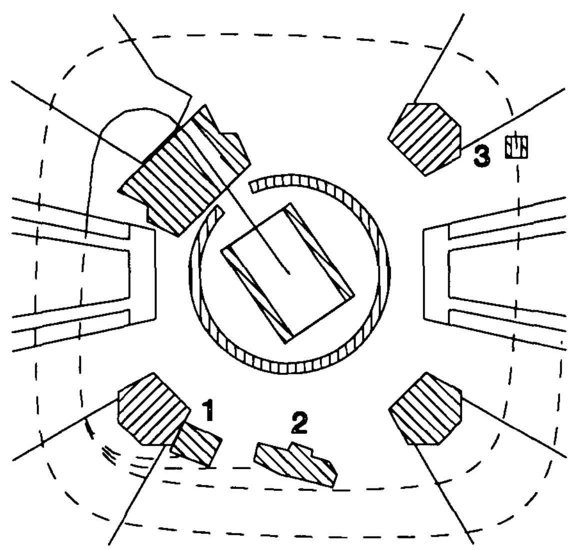

Fig. 1. **Midplane section of the center region of injector 2.** The beam starts in the center, bending from the vertical into the horizontal plane. After the 135° bend in the tip of the first sector magnet, the beam crosses a pair of acceleration gaps. Acceleration or deceleration depends on phase and produces a fan-out of the particles after sector magnet 2. The initial phase (and intensity) selection is made with collimators KIP1, KIP2(1,2). The additional collimator RIL2 (3) improves the phase selection.

2. MOTIVATION

Various upgrade programs underway at PSI will require beam intensities of 1 to 1.5 mA at 590 MeV.[1)2)] In the first years of operation 870 keV DC beams of 8 to 10 mA were used in the center region of injector 2 to get intensities of 0.8 to 1 mA extracted. With flat-topping extending over 10% of the RF phase, a corresponding fraction of the DC beam was expected to be usable for acceleration. However, while 1 mA extraction was achieved by 1985, beams above 0.5 mA were not of a quality good enough for the 590 MeV ring.

Improving the beam quality at high currents became the primary goal, with the two possible approaches being an increase of the DC beam current or use of a buncher. As bad beam quality could be partially due to the wide phase acceptance needed to produce high intensity beams, these two methods to enhance the local current density were tried early on in the attempt to improve extracted beam quality. Increasing ion source output current above 10 mA was found not to be possible without worsening beam quality in the center region. This, in turn, ruined phase selection and therefore canceled any advantages of a potentially narrower half-maximum phase width. Initial experience with bunching showed minimal or negative results. This inspired an extensive model- and experimental- based examination of bunching under space-charge conditions and of the phase selection mechanism acting on the resulting bunched beam.

3. BUNCHING MODEL RESULTS

Two different levels of buncher modeling were used. One was a simple linear model which assumes no space charge forces; only the momentum variation from the buncher acts on longitudinal motion. A more realistic model written by Rick Baartman[3)] was used to treat the "one-dimensional" space charge case. In this model, energy variations and the resulting longitudinal motion of particles in a beam line are simulated by calculating space charge forces as a function of average beam diameter, beam tube diameter and of the longitudinal density distribution.

Figure 2 shows the simulated effect of a buncher in a diagram plotting momentum deviation vs. phase for four different cases: with and without space charge forces and for 4 kV and 7 kV amplitudes on the double gap buncher. The intensity distribution can be derived from dot spacing, which corresponds to an initial phase separation of 3.6 degrees at the buncher (1% of DC beam). In all of the cases shown, the limit to acceptance is not due to the restricted phase width of the acceptance window, but to the small acceptance in momentum spread of about ±0.15%, imposed by the requirement for high beam quality at extraction.

In the 4 kV, "mild" bunching case of the simple linear model, the phase × momentum spread window can accept only 10% of the initial DC beam, the same fraction as can be accepted without bunching. With space-charge effects, momentum spread is reduced, allowing 16% of the DC beam into the window.

Assuming a buncher at 7 kV, the situation is dramatically different. Without space-charge, acceptance is minimal, due to the large momentum spread. However, with space-charge effects included, the model shows that the resultant momentum damping allows 25% acceptance into the same window. This quite different behaviour in the space-charge case is due to the fact that over a ±6 degree range, space-charge momentum "braking" results in a virtually mono-energetic beam of high intensity. We call this situation "space-charge-limit bunching" (SCL bunching).

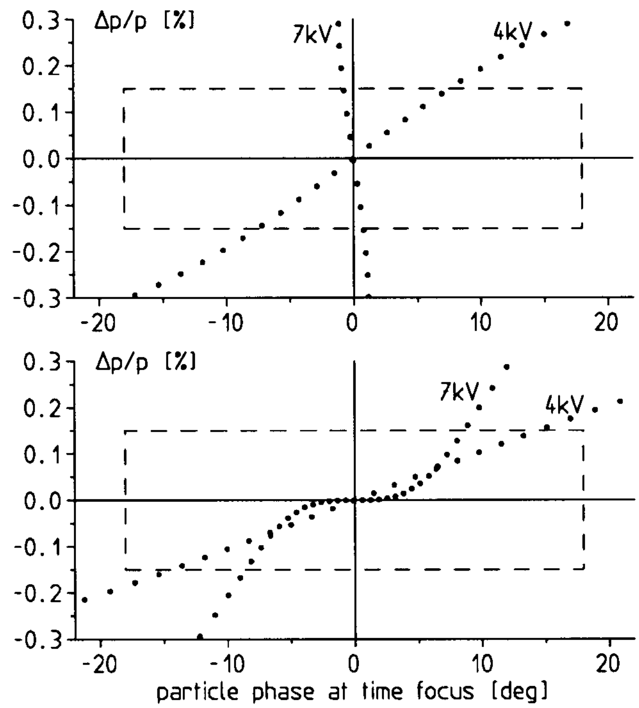

Fig. 2. **Momentum variation vs. phase at time focus** for a linear buncher model (above) and a buncher model with longitudinal space-charge forces (below). For both models, two cases, for voltages of 4 kV and 7 kV, are drawn. The effect of space-charge forces is to produce a highly monoenergetic kernel of intense beam.

As a first step in examining the applicability of a SCL bunched beam in injector 2, plots such as those in fig. 3 were generated by a simple phase selection model which adds the momentum spread from the buncher simulation to the energy gain of the beam in the first acceleration cavity and follows the drift for a distance equal to that from the acceleration gaps to KIP2, the main phase selecting collimator. In fig. 3a, the case of "mildly" bunched beam, one sees the energy vs. phase relation at the location of KIP2 as a slightly distorted cosine peak, 3 degrees phase-delayed. In the case of SCL bunched beam, as shown in fig. 3b, the cosine becomes extremely distorted. The sharp rise in the momentum of trailing particles compensates for the fall-off in the resonator voltage! The phase width over which the SCL bunched beam has near-zero momentum spread is effectively doubled. The results of this simple model stimulated a more detailed examination of the phase selection mechanism.

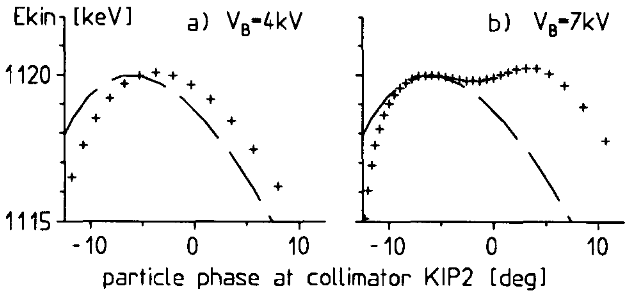

Fig. 3. **Particle energy as a function of phase at KIP2** (after half a turn). Energy values result from adding 870 keV to the buncher simulation results (including longitudinal space charge forces) and to the phase-dependent energy gain of the first accelerating cavity.

4. INJECTOR MODEL RESULTS

Injector 2 beam dynamics are modelled by a simulation called MATADOR. (MAtrix Techniques for Acceleration studies and Display of ORbits).[4] In this program the positions in radius and phase of up to several hundred particles are calculated during acceleration process. To speed up the simulation, transfer matrices are used to calculate the change of particle positions from one azimuth to the next, stepping over large sections of a turn in one operation. Beam simulations with MATADOR initially used a uniform-density, mono-energetic column of particles, using the centerline of resonator 1 as the starting point for particle tracking. In order to investigate the implications of SCL bunched beam, MATADOR was modified to allow input of beams with correlations between radial position, momentum, and phase, as well as non-uniform intensity distributions. Additionally, radial cutting of beams by collimators was entered into the simulation. Including the dispersive effects of the 135° bend in the tip of sector magnet 1, phase and momentum information from the buncher model was used to generate a more realistic sample input beginning at the first acceleration gap of resonator 1.

Important results from simulations for SCL bunching are given in fig. 4. Figure 4a shows a "snapshot" of the beam (from above) at the azimuth of KIP2 ($\Theta = 135°$) on the first orbit. If KIP2 is placed at the radial location indicated by the horizontal broken line, the beam at $\Theta = 235°$ (at the second gap of Resonator 3) is as shown in fig. 4b (faint and solid lines). Notice the asymmetrical nature of the initial phase cut. The phase tails of this beam, when tracked to full radius will spread over such a large phase space volume that clean extraction becomes impossible. However, if a second cut is made using the new collimator RIL2, the simulation shows a well-defined pattern at extraction with a net acceptance of about 35% of the DC beam.

The effect that KIP2 only makes a clean cut for the leading phase edge and generates long tails for the lagging phases, occurs for DC beams and "mildly" bunched beams as well. Based on these results, a second phase cutting collimator was installed in injector 2. A quick solution was to mount a collimator block on an already-installed radial probe mechanism, labelled RIL2 in fig. 1.

Located at an azimuth of 250° it was near enough to a 90° betatron phase advance downstream from KIP2 to have the desired effects. Plenty of cooling power is required for RIL2; the simulations predict that for optimal phase selection the intensity cut away by RIL2 is approximately 1/3 of the extracted beam intensity.

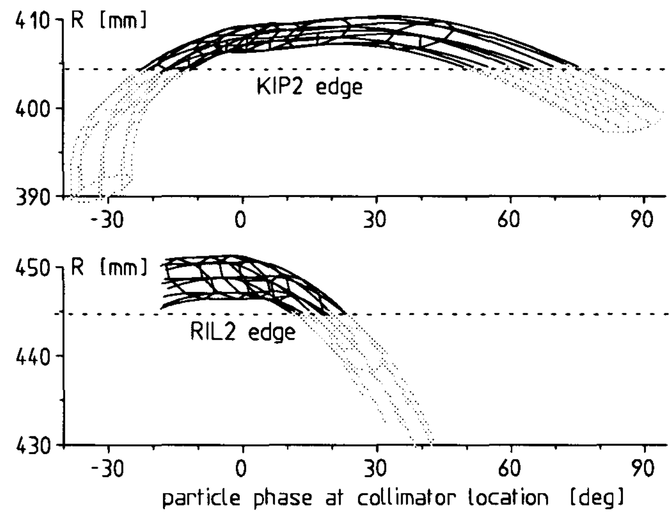

Fig. 4. **Phasespace cutting by the radial collimators KIP2 and RIL2 for a SCL bunched beam.** The radial and phase distribution of a simulated beam before (faint lines) and after (solid lines) being cut by KIP2 (135°) and by the new collimator RIL2 (235°).

5. RESULTS AND CONFIRMATION OF PREDICTIONS

Most of the beam measurements made to compare the simulations to the real beam behaviour showed a good agreement between measurements and simulations. The agreement was even better than could be expected taking into account the substantial simplifications used in the models. A critical point of the setup that had been predicted by the MATADOR runs was the radial focusing of the 870 keV beam in the first resonator and at the collimator KIP2. The beam optical behaviour of the 870 keV beamline was therefore analyzed in detail to establish the proper settings of optical elements. In this analysis the need to set the optics in a vertically dispersionless mode was detected. It can not be simulated by the one-dimensional buncher model, but is intuitively clear that if leading and lagging parts of a SCL bunched beam are bent onto different vertical positions the "braking" force is no longer acting in the longitudinal direction.

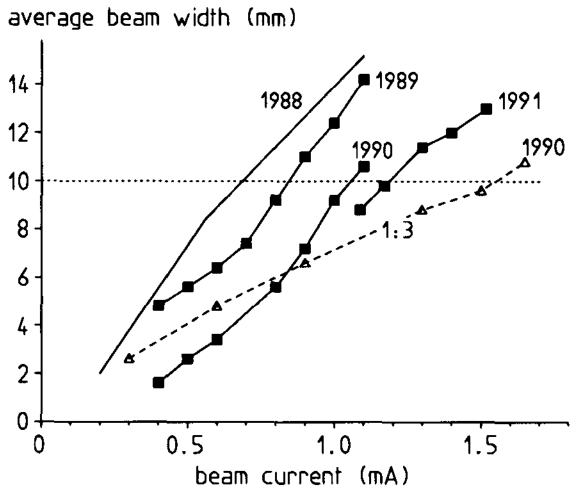

Fig. 5. **Average radial beam width at extraction vs. beam intensity.** The "wavefronts" progressing downwards and to the right indicate the best beam settings that could be achieved in terms of the high intensity and small beam width. The dashed curve (marked 1:3) represents equivalent intensities of beams where only one out of three pulses is accelerated. The critical value of 10 mm for the beam width marks the beam quality required for acceleration in the 590 MeV ring cyclotron.

An excellent overall test of the validity of these investigations is shown in fig. 5. Each line gives the correlation between the smallest beam width and the extracted beam intensity defined by a series of best beam setups in a particular period. The progress from 1988 to 1989 can mainly be assigned to the usage of the buncher with settings based upon simulations, but without the new collimator RIL2. The installation of RIL2 brought along the big progress from 1989 to 1990, where for the first time a beam of 1 mA was produced with sufficient quality for the ring cyclotron. Stabilizing the buncher phase, as well as the RF voltage and phase at high currents, gave another substantial improvement and enabled the extraction of 1.5 mA in 1991, again using a strongly bunched beam.

A direct measurement of a SCL beam, compared to an unbunched beam at the same high intensity is shown in fig. 6. Time structure information is obtained from counting protons elastically scattered on a thin carbon fibre placed in the beam. Several of these measurements taken for different radial positions of the fibre are combined to give a "top view" and a phase profile of the beam at extraction. The beam obtained with SCL bunching really shows a very narrow phase width beam of extremely high local current density.

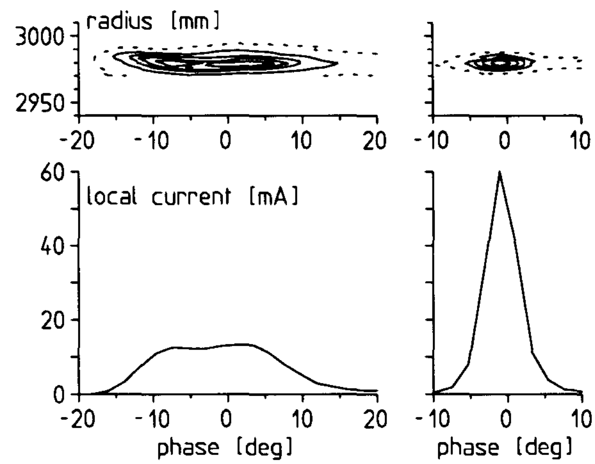

Fig. 6. **Measured phase width of two different beams at extraction.** Comparing the results of the radial and time structure measurements for an unbunched beam to the results for a SCL bunched beam show the high intensity narrow phase beam obtained with bunching. In both cases, the extracted intensity is 0.9 mA.

6. CONCLUSIONS

All of the above results support the conclusion that "space-charge-limit bunching" (SCL bunching) is in fact occurring in a manner substantially as discussed above and is a useful approach to increasing intensity without decreasing beam quality. Proper dispersion matching in the injection line and careful phase selection are necessary conditions for applying this technique. It is quite surprising that a such simple bunching model can give such good results. A full 6 dimensional simulation of this phenomenon may yield further useful predictions. The survival of such an intense beam, approaching 60 mA DC equivalent, through injector 2, challenges previous notions and simulations of space-charge effects under such conditions and warrants further investigation.

7. REFERENCES

1) Schryber, Urs, "Upgrading the PSI Accelerator Facility for High Intensity Operation." 3rd European Accelerator Conf., Berlin, 1992
2) Stammbach, Th., "Experience with the High Current Operation of the PSI Cyclotron Facility." this conference.
3) Baartmann, R., "SPUNCH - A Space Charge Bunching Computer Code." Proc. 11th. Conf. on Cyclotrons Tokyo, Japan. 1987, p. 283.
4) Adam, S., "Calculation of Space Charge Effects in Isochronous Cyclotrons." IEEE NS-32, 2506 (1985) and Thesis 7694 ETH Zurich. 1985.