VICKSI BEAM BUNCH PREPARATION

W. Pelzer
Hahn-Meitner-Institut Berlin GmbH
Glienicker Str. 100, 1000 Berlin 39, West Germany

A description of the VICKSI beam bunching system is given.

VICKSI beam properties

Accelerator-combinations of Van de Graaff-injectors and cyclotrons can provide a large variety of heavy ion beams with high energy resolution. The VICKSI-design[1] allows energy spreads of less than one per mill. This goal was expected to be achieved by injecting the beam into the cyclotron within less than 6 degrees of phase width on top of the cyclotron-rf-sine wave, if at the same time the magnetic field satisfies the isochronous condition. Since the cyclotron-rf-frequencies range from 10 to 20 MHz, the time spread of the extracted beam bunches would be less than 1 ns.

This design aim has been reached with both VICKSI injectors. The beams developed up to now with our new UD-tandem injector typically have a time spread at the target of about 800 ps. The energy width for VICKSI-beams on target with the CN-Van de Graaff-injector is about $5\cdot10^{-4}$ with the standard setting procedure, corresponding to 500 to 700 ps time spread; down to 250 ps could be achieved with special settings, but always at cost of beam intensity.

With the narrow 6 degrees phase window of the cyclotron, 59 from 60 ions from the source are emitted at the wrong time. In addition, the penning sources[2] are rather limited in output, especially at higher charge states, and stripping typically costs another factor of three in beam intensity, when our Van de Graaff-injector is used. With the tandem injector it is even a factor of ten. Since several experiments require longer beam-off periods than the 50 to 100 ns pulse distance preset by the cyclotron-rf, the VICKSI pulsing system[3] extends these periods from 100 ns up to the ms-region by deflecting the unwanted bunches onto slit jaws. Not only under these conditions the available number of particles in each bunch often is too low; necessary diagnostics like internal cyclotron phase probes fail with total beam currents below 1 enA.

Whereas stripping efficiencies cannot be much more improved, ion source development offers promising directions, like an ECR-source for Van de Graaff-terminals. To gain intensity in the beam pulse by bunching is another way, which has been joined at VICKSI from the beginning (see fig. 1): For each injector three bunchers are used to shift more than 50% of the ion source dc output into the correct phase interval for the cyclotron, thus reducing the losses due to wrong phase from a factor of 60 down to a factor of 2. This leads to a standard beam transmission for analyzed Van de Graaff injector beams to analyzed cyclotron output of about 10%.

Bunching system layout

Figure 1 gives an overview on VICKSI, indicating the type and location of each buncher, and schematically showing the beam intensity versus time behaviour at several beam line positions. All bunchers are driven with a sine wave, modulating the velocity of

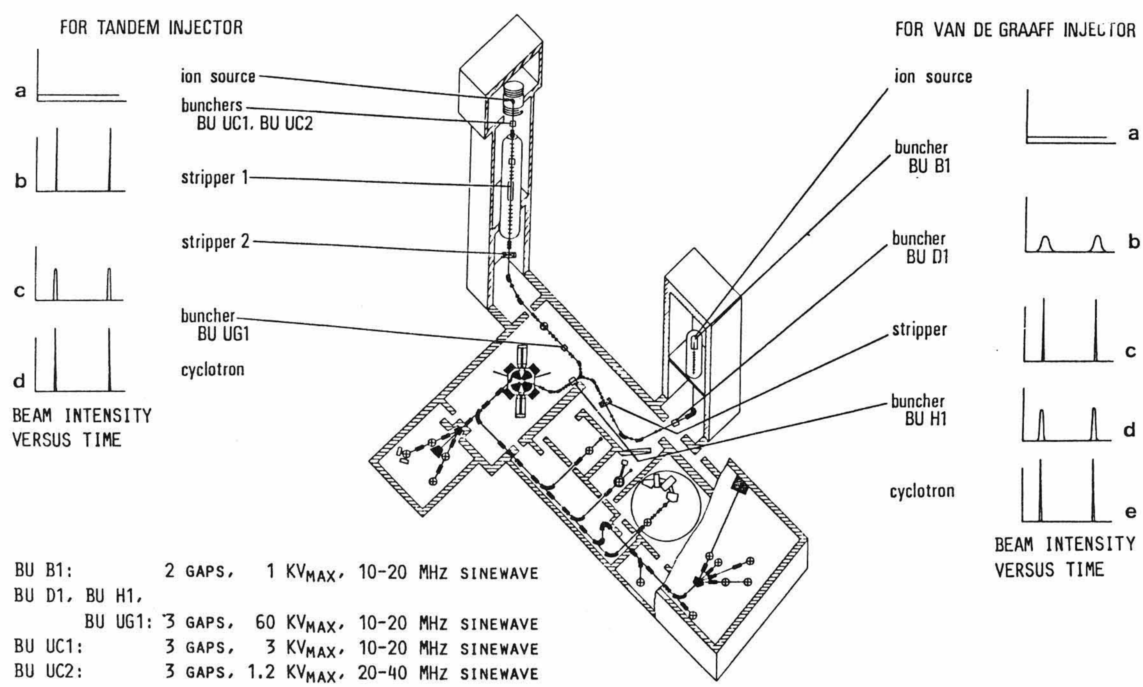

Fig. 1: Layout of the VICKSI bunching system

the ions while these are passing through gaps between the buncher electrodes. After a certain drift length the velocity modulation leads to a "focussing" of the ions in time: The dc ion beam develops a pulse structure. Velocity modulation also means additional energy width: VICKSI beams have injection energies with a spread of up to 1%. Nevertheless, the energy spread of the extracted ion beams stays well below one per mill because of the relative decrease due to further acceleration.

For the Van de Graaff, bunching[4,5] begins at the high voltage terminal with buncher BUB1, which shifts about 60% of the dc-beam from the ion source (a) into a 60 degrees wide phase interval with respect to the cyclotron rf period. The high energy gain of the beam by passing the injector tube reduces the relative energy spread. This allows the beam pulses after the injector to be considered again as mono-energetic with respect to the second bunching at BUD1: The residual energy spread is always less than 10% of the value added afterwards by BUD1. Since the sine wave is linear for ±30 degrees around the zero crossings with an error of less than 1%, the 60 degrees wide beam pulses at BUD1 (b) can be bunched with 100% efficiency down to less than 6 degrees at the stripper (c). Here the time focus is needed to reduce the deterioration of the phase space due to energy straggling at the stripper foil[5]. After passing the stripper the beam diverges again. At the third buncher BUH1 (d) this effect is compensated and the beam is refocused to less than 6 degrees phase width at the cyclotron injection (e).

The main part of the ions with wrong phase is lost on the slits used for transit time regulation (see below) of the terminal buncher. The remaining part, with about 180 degrees phase deviation, is stopped on phase slits after the first turn in the cyclotron.

For the tandem injector[6,7], a slightly different scheme has been followed. Here the ion source delivers negatively charged particles, which have to pass two strippers: The first (in the high voltage terminal of the tandem) is needed for the change to positive charge. The second (after the tandem) gives the necessary rise of charge state to the values needed for cyclotron injection. To avoid the additional beam distortion by stripping a broad beam, there must be formed a pulse with narrow time spread already in the tandem. Therefore two bunchers BUUC1 and BUUC2 are installed in the beam guiding system between the ion source high voltage platform and the tandem. They form a "double drift" bunching system[8]. While BUUC1 is driven at the same frequency as all the other bunchers and the cyclotron-rf, BUUC2 runs at the second harmonic. With a drift space between the two bunchers of about one sixth of the focal length of the total system, the overall velocity modulation of the ion beam can be made linear within less than 1% over a 220 degrees phase range. This allows more than 60% of the dc output of the ion source (a) to be brought into beam bunches as narrow as 6 degrees (referred to the cyclotron-rf-period) in the tandem (b).

In the high voltage terminal gas is normally used for stripping, whereas stripper 2 is usually operated with foils, which gives rise to a higher energy straggling. This causes the beam pulses to diverge to a width of up to 25 degrees (c). Compensation is achieved with BUUG1, which rebunches the ion beam again down to 6 degrees pulse width as needed at the cyclotron injection (d).

Ions with wrong phase are mainly stopped on the slits used for transit time regulation (see below). A phase slit at variable position in the cyclotron will be inserted to allow for the complete cleaning from the rest of unwanted particles with wrong phase.

Buncher design

Electrodes. The ion beams pass the buncher electrodes with different velocities, depending on the energy and mass of the chosen particle. Since also the bunching frequencies vary up to a factor of two, the electrodes have been built to provide effective velocity modulation over a wide range of frequencies, masses and energies. Figure 2 shows an example from

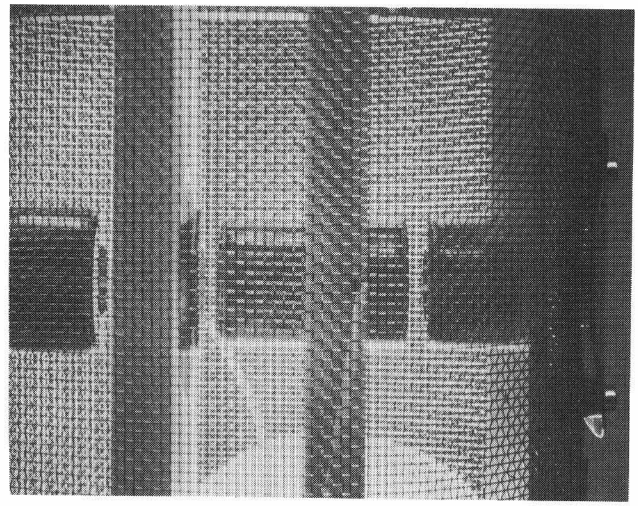

Fig. 2: Drift tube assembly, prebuncher BUUC1

the first tandem buncher BUUC1 (for dimensions see also fig. 3 and 5). Two copper tubes with different length and diameter are mounted in series, forming three modulation gaps. Due to the push/pull operation mode the middle gap between the two tubes holds twice the voltage than the two other gaps to the outer electrodes at ground potential. Simple shifting of the middle gap out of the center position leads to a big increase of operation range[9]. With both tubes at equal length $L_1=L_2$ and a transition time of the beam through one tube corresponding to half a period of the operating frequency, a maximum of four times the buncher voltage modulates the beam. If a voltage gain of a factor of two is still sufficient, the transit time may be changed between 0.5 to 1.5 of the optimum value. However, with the tubes at unequal length this range can be increased. For $L_1=2L_2$ as an example, transit time changes between 0.5 to 2.5 of the optimum value are allowed. With $L_1=1.5L_2$ and a minimum tolerable voltage gain of 1.75, the range increases even up to values between 0.45 to 4.5 of the optimum transit time. Therefore all VICKSI bunchers are equipped with 3-gap electrodes. The only exception is the terminal buncher BUB1 with a 2-gap scheme. Here the acceleration potentials can be easily adopted to provide always the optimum particle velocities.

High voltage bunchers. The three bunchers in the injection paths to the cyclotron are built almost identically (fig. 3, 4). At the 20 mm wide middle gap they deliver up to 60 kV to the beam. This voltage is supported by an rf power of less than 5 kW, since resonance circuits are used to transform the load resistance down to the 50 Ohm input impedance and to compensate for the parasitic capacities. These are in the order of tens of picofarads. Therefore different coils are used to cover three overlapping frequency bands in order to reach the required operating range from 10 to 20 MHz. The high voltage circuit has a Q of about 1500; automatic tuning to resonance must be applied during operation in order to compensate for temperature drifts. Cooling of the coils and the high voltage terminals is achieved with demineralized water. All these parts are in air; only the buncher

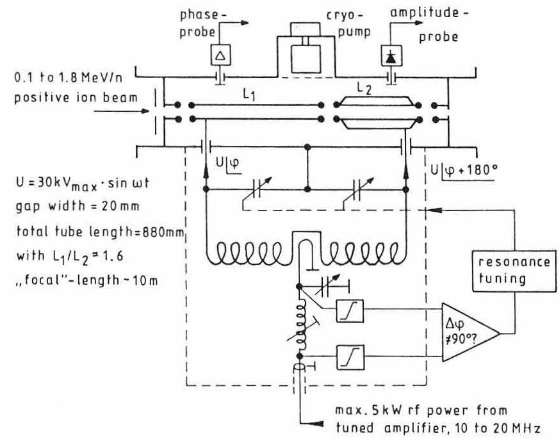

Fig. 3: Block diagram of a high voltage buncher

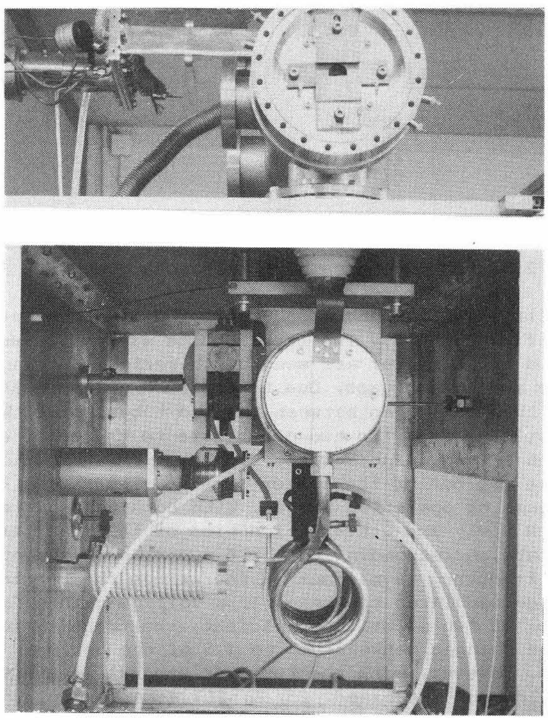

Fig. 4: Resonance circuits of BUH1

drift tubes are in vacuum, decoupled from the other components by two feedthroughs made of teflon, which is partly metallized to lower the electric fields at the insulator surface.

A 10 kW tuned power amplifier made by HERFURTH delivers the necessary rf drive to the buncher circuits. The controls consist mainly of modified SCANDITRONIX drive units from the cyclotron. These electronics allow amplitude regulation to better than one per mill within a range between maximum value and 1/10 of that. The phase can be set to any value within one period of the operating frequency, and is regulated to better than 0.1 degree.

Tandem double drift bunchers. In the beginning the installation of a sawtooth-buncher on the ion source high voltage platform has been considered. To obtain good linearity over a wide frequency range a low impedance design seemed to be necessary. This allows sufficient modulation voltage only with excessive rf power; therefore a double drift scheme[8] was applied (fig. 5).

Rf power of less than 300 W is needed to drive BUUC1. The corresponding value for BUUC2 is 150 W. The bunching electrodes are part of a resonance circuit, which is automatically tuned during operation. An input circuit provides 50 Ohm impedance to the broadband amplifiers made by HERFURTH. The rf power is lost mainly in the two 100 Ohm resistors for input matching, since the coupled load resistance is in the order of KOhms. Only the input resistors are watercooled.

The inner diameter of the electrode tubes is 20 mm because of the beam spot size of more than 10 mm at the buncher positions. The strong penetration of the electric fields into such electrode tubes as well as the long transition time of the ions through the gaps deteriorate the bunching effect[8,10,11]. For compensation 20 µm thin wire grids from tungsten with a 3 mm spacing have been inserted. The lifetime of these grids is not yet sufficient: During setting up

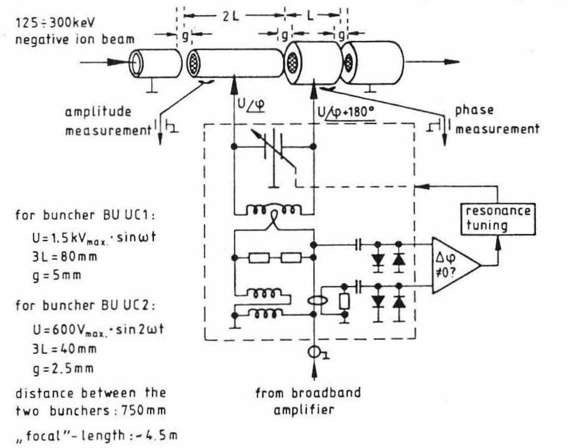

Fig. 5: Block diagram of the tandem prebunchers

the beam may be sharply focussed to the grid wires, which in turn gives rise to a stronger sputtering for a single wire than estimated. Especially for slow and heavy ions broadening of the pulse width is expected if the grid wires are missing. However, a carbon beam could be bunched down to 600 ps even with all wires taken away.

The distance between the two bunchers with respect to the total focal length of the system effects the bunching efficiency[8]: The choosen 1/5 ratio gives about 65% of the dc ion source output into the 6 degrees phase window.

Transit time regulation. For both injectors the energy of the analyzed ion beams is stabilized with a slit regulation system. This does not necessarily mean, that the transit time of the particles through the accelerating tube keeps constant. A shorted tube section on the low energy side for example results in a transit time shift in the order of up to 10 ns. Fluctuations in the order of several ns can often be observed. The quality of the cyclotron beam would be severely affected by such instabilities: For example, a change of injection phase by five degrees causes distinct changes of the turnpattern (fig. 6).

To correct for these transit time instabilities a separate slit regulation system is added to both injectors: The energy modulation by a buncher leads to a broadening of the beam after a following dipole magnet, which yields equal current readings from centered slit jaws in this position. If the ion beam has been prebunched to a wrong injection phase, then the following high voltage buncher (set to proper phase) adds an energy shift to the particles, which in turn shows up as a difference of slit current readings after the next dipole. By regulating these slit current differences down to zero with corresponding shifts of the phase reference for the prebunchers, the arrival time of the beam bunches at the cyclotron can be synchronized with the cyclotron-rf-frequency.

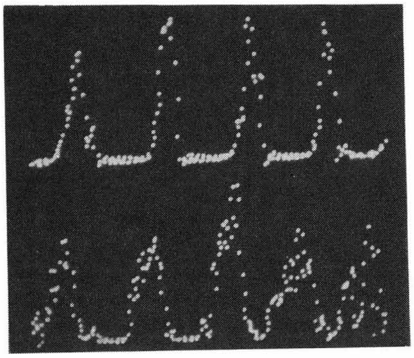

Fig. 6: Cyclotron turn pattern, 1650 to 1700 mm
top: with optimum injection phase
below: shifted five degrees away

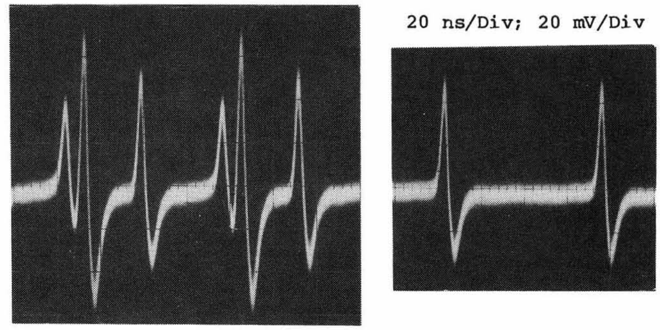

Fig. 7: Capacitive pick up signals of tandem beam bunches. Left: with several charge states. Right: unwanted charges suppressed

Under normal conditions this system improves the stability of the injection phase of the beam bunches by about a factor of ten. However, due to a coupling between beam energy and injection phase in the regulation circuit, an energy shift of the analyzed beam would show up as a transit time shift. Therefore excellent energy stabilization is an important condition. Our CN-Van de Graaff-ripple is presently regulated down to $\pm 5 \cdot 10^{-5}$. With the tandem-injector, energy drifts are still a problem due to a less effective terminal potential stabilization system. We expect to solve this problem by changing to the same electronics as used for the CN-Van de Graaff-injector.

Direct regulation of the prebuncher phase reference to the measured injection phase would eliminate the unwanted coupling mentioned above. This scheme is object of further VICKSI development.

Operation criteria

Setting up and correction of the bunching system depends on the available measuring tools. At VICKSI, capacitive pick ups, the radial differential probes in the cyclotron and the detection of scattered particles or beam induced γ-rays are used.

The last instrument gives detailed and exact information on the time width of the beam pulse. It is mainly used at the target areas during setting up and for checks after experiment runs. For additional checks during operation a teststand has been installed after the cyclotron analyzing magnet, where the beam hits a permanently moving finger probe wire. However, for every new setup the results from these measurements have to be calibrated against the values obtained from the target area, since due to the VICKSI beam optics the time spread of the beam bunches is worse at the teststand area than actually reached on target[12].

The turnpatterns produced by the radial differential probes in the cyclotron give a measure for proper injection phase and good pulse shape of the accelerated beam bunches. For example, a five degree change of injection phase away from the optimum value is a clear change to the worse (fig. 6). With respect to the buncher amplitudes, a distinct smearing out effect of the turnpattern can be observed for a 10% change away from the optimum amplitude value.

Status and stability of bunching are at present easily observed with capacitive pick ups[13]. Positioned in the injection paths close to the strippers, the 20 mm short copper tubes pick up sharp pulse signals from the well focussed beam bunches when entering and leaving the tube. A minimum of 40 dB wideband rf amplification normally delivers sufficient amplitude to drive a spectrum analyzer or a high speed scope for monitoring.

Figure 7 shows an example of signals delivered from the pick up inserted in the tandem beam path directly before the second stripper. At the high-voltage terminal the gas stripping produces different charge states from a carbon beam. With prebunching before the tandem, three charge states appear at the pick up after the tandem as beam pulses with different time of arrival (left). Switching on the offset-quadrupole for charge state selection in the tandem terminal eliminates the unwanted charge states (right).

Besides fast and accurate tuning of the offset-quadrupole this capacitive pick up allows also for a quick setting of the amplitudes and the phase relation between the two prebunchers. The amplitude- and phase-values for the last bunchers before the cyclotron injection (BUH1 resp. BUUG1) are tuned by optimizing the turnpattern of the internal cyclotron beam.

To obtain beam bunches with time spreads below 500 ps special settings are necessary: The injection phase of the cyclotron beam is shifted a few degrees away from the top of the accelerating rf sine wave. This induces an energy/time-correlation to the extracted beam. Cutting down the energy width of the beam with slits behind the analyzing magnet leads to a reduced time width. We observed half the time spread at cost of half the beam intensity. In addition, the extracted beam is more sensitive to instabilities. Therefore calculations in another promising direction, based on detuning of the magnetic field in the cyclotron away from isochronism[14], are object of further VICKSI development.

References

1. Maier, K.H.: Proc. 7th Int. Conf. on Cyclotrons and their Applications. Basel: Birkhäuser 1975, p. 68-75
2. Arndt, P., et.al.: IEEE Trans. Nucl. Sci. NS-22 (1975) 1715
3. Pelzer, W., Ziegler, K.: Atomenergie/Kerntechnik Vol. 46 (1985) No. 3, p. 147-154
4. Hinderer, G.: HMI-report HMI-B 165 (1975)
5. Hinderer, G., Maier, K.H.: IEEE Trans. Nucl. Sci. NS-22 (1975) 1722
6. Busse, W., et.al.: Nucl. Instr. & Meth. 184 (1981) 229-232
7. Busse, W., et.al.: Nucl. Instr. & Meth. 220 (1984) 26-29
8. Milner, W.T.: IEEE Trans. Nucl. Sci. NS-26 (1979) 1445-1449
9. Hinderer, G.: Private communication (1979)
10. Skorka, S.J.: IEEE 81 / CH 1639-4 (1981) 130-138
11. Lynch, F.J., et.al.: Nucl. Instr. & Meth. 159 (1979) 245-263
12. Lehr, H., et.al.: HMI-report HMI-B 259 (1978)
13. Strehl, P., et.al.: GSI-report GSI 79-13 (1979)
14. Gordon, M.M.: IEEE 84 / CH 1996-3 (1984), 279-287