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THE BEAM-MATCHING SYSTEM BETWEEN PRE- AND MAIN-ACCELERATOR FOR THE VAN DE GRAAFF-CYCLOTRON-COMBINATION VICKSI

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Summary

The matching system connects the Van de Graaff preaccelerator with the isochrounous split pole cyclotron of the heavy ion accelerator combination VICKSI and prepares the beam for injection into the cyclotron. The charge state of the ions is increased by a stripper (gas or carbon foil). This however enlarges the phase space occupied by the beam due to angle- and energy straggling. To minimize this deterioration of beam quality a sharp focus at the stripper is provided in all three dimensions. A longitudinal (time) focus both at the stripper and in the center of the cyclotron is achieved by means of two identical clystron-type bunchers.

The magnetic focusing system between the two bunchers contains two doubly achromatic bending units of 90 degrees. Telescopic focusing is used onto the stripper and from the stripper to the second buncher. The last section just before the cyclotron comprises one more bending unit and several quadrupoles for dispersion matching and adapting the horizontal and vertical phase space for injection.

The VICKSI accelerator

At the Hahn-Meitner-Institut Berlin the heavy ion accelerator combination VICKSI (Van de Graaff Isochron Cyclotron Kombination für Schwere Ionen) is under construction.[1] The status of the project is presented in a separate contribution to this conference[2]. The system consists of a 6 MV Van de Graaff as injector and a split-pole-cyclotron. This combination is able to accelerate ions of mass $10 \leq A \leq 40$ up to an energy of 200 MeV. Beam currents of 10^{12} particles/sec at an energy resolution of $\Delta E/E = 10^{-3}$ are anticipated.

The Van de Graaff accelerates doubly charged ions to $E_i \leq 12$ MeV. The ions are stripped and further accelerated in the cyclotron to $16.8 \cdot E_i$. The cyclotron consists of 4 separated 50° magnets and two 36° Dees. The energy capability of the magnet is $A \cdot E/q^2 = 100$ MeV.

Fig. 1 shows the layout of the accelerator combination. The vertical Van de Graaff stands above its analyzing magnet (marked CN-Anal. Mag.). The subject of this article is the beam matching system from this point to the cyclotron.

The beam matching system

The purpose of the system is to bring the preaccelerated beam from the Van de Graaff to the cyclotron and to change its properties according to the requirements of the cyclotron at injection. The main condition for all heavy ions is to increase their charge state sufficiently that the maximum magnetic rigidity of the innermost orbit of the cyclotron is met. Therefore a combined gas- and carbon foil stripper is provided (str of fig. 1). For ions up to A=20 the gas stripper can be used. For heavier particles a foil stripper is more favourable since the most abundant charge state which lies one to two units higher than for a gas stripper can be used. However the carbon foils cannot be made much thinner than 10 μg/cm^2 and the resulting energy - and angle straggling is rather high. These effects have been measured at HMI. A preliminary report[3] is given by B. Efken et al. in the internal VICKSI Statusbericht 4.

The straggling increases the sixdimensional phase space occupied by the beam. The amount depends however strongly on the beam properties at the stripper. If we for instance regard the vertical phase plane and assume a waist of the beam at the stripper the emittance behind the stripper is given by the original beam size times the increased extend in angle. This new angle results from quadratically adding the original angle and the angle straggling. Therefore the emittance will be largely increased if a wide nearly parallel beam impinges on the stripper and little for a sharp focus. The same holds for the horizontal and longitudinal phase planes. This property together with the Van de Graaff and cyclotron data determined the design of the system.

The longitudinal phase space

The focusing system in longitudinal phase space comprises two clystron-type high frequency bunchers (b1 and b2; see fig. 1). At third one is installed in the high-voltage terminal of the Van de Graaff. A sine wave of the cyclotron RF frequency (8 to 20 MHz) is applied to all three.

The terminal buncher modulates the dc-beam from the ion source in a way that about 60 % of the beam intensity behind the Van de Graaff lie within ±30°. For that part of the beam the bunchers b1 and b2 are quite linear (because sine is nearly linear within ±30°) and can be treated as thin lenses for the longitudinal phase space. The first buncher b1 produces a longitudinal focus at the foil stripper in order to minimize the enlargement of the longitudinal phase space due to energy straggling. Behind the stripper the pulse length increases again. The second buncher b2 refocuses the beam so that the pulse length in the center of the cyclotron corresponds to ±3° in order to achieve for the beam from the cyclotron a small energy spread which roughly is proportional to the square of the pulse length.

The voltage amplitude of the bunchers needed for proper focusing depends on the available length of the system. The length of the choosen configuration is considerably longer than the distance between the two accelerators. The amplitude on the buncher tubes therefore could be limited to 60 KV. Another advantage of the system over a more or less direct connection is the possibility of cleaning the beam from unwanted parts (see section "Energy and phase selection").

The horizontal and vertical phase space

For the transformation of the beam in the horizontal and vertical direction nine quadrupol-units (q_1 to q_9) and six dipoles (a to f) are used. The properties of these magnetic elements are calculated with the computer program TRANSPORT[4]. The system before the stripper is designed for a maximum magnetic rigidity of the ions of $K = A \cdot E/q^2 = 280$ corresponding to a single charged argon beam of 7 MeV. Behind the stripper the K-value is determined by the first orbit in the cyclotron as 7.2. In fig. 2 the beam envelopes in the longitudinal, vertical and the horizontal direction are shown. Starting point for the transverse phase space is the stigmatic image of the CN-analyzing magnet at slit s1. On the way up to the second buncher b2 the beam is "prepared" for the injection into the cyclotron. The elements behind b2 are then used to adapt the beam to the requirements at the entrance of the cyclotron. Some features of the system are discussed now in more detail.

Achromatic beam guiding. The "preparation" part of the system between s1 and b2 contains the two achromatic bending units a-q2-b and c-q5-d. Each unit has reflection symmetry in respect to a plane through the middle of the quadrupole perpendicular to the beam axis. The first half consists of a 45^o-sector magnet, the pole-face rotation at the end of this magnet, a short drift space and the first half of the quadrupole magnet.

The transformation properties of systems with special symmetries are described by J. C. Herrera and E. E. Bliamptis[5]. In this case the requirements of vanishing angular dispersion ($R_{26} = 0$ in TRANSPORT nomenclature) in the symmetry planes of these units leads to zero radial- and angular dispersion ($R_{16} = R_{26} = 0$) for the whole bending units which therefore can be regarded to first order as achromats. The condition $R_{26} = 0$ in the symmetry planes is achieved by horizontal focusing with the quadrupoles q_2 and q_5. The entrance and exit pole-face rotations of the 90^o-bending units do not belong to the achromats as they produce only quadrupole field components in a region with zero dispersion. Together with the exit pole-face rotation of the first magnet (a resp. c) which is equal to the entrance pole-face rotation of the second (b resp. d) each bending unit therefore has three additional parameters which are used for transverse focusing (see "telescopic optics").

As only the two achromats contain dipole components the beam line between s1 and the entrance of the dipole magnet e is to first order achromatic except for the path inside the bending units. This achromatic beam guiding is necessary essentially for two reasons:

1. The first order transformation matrix for a magnetic system in which the x-z-plane is a symmetry plane for all elements can be written in general (TRANSPORT nomenclature)

$$R = \begin{bmatrix} R_{11} & R_{12} & 0 & 0 & 0 & R_{16} \\ R_{21} & R_{22} & 0 & 0 & 0 & R_{26} \\ 0 & 0 & R_{33} & R_{34} & 0 & 0 \\ 0 & 0 & R_{43} & R_{44} & 0 & 0 \\ R_{51} & R_{52} & 0 & 0 & 1 & R_{56} \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \qquad (1)$$

The dispersion elements R_{16} and R_{26} are connected to the path length elements R_{51} and R_{52} via two linear equations:

$$\begin{bmatrix} R_{51} \\ R_{52} \end{bmatrix} = \begin{bmatrix} R_{21}-R_{11} \\ R_{22}-R_{12} \end{bmatrix} \cdot \begin{bmatrix} R_{16} \\ R_{26} \end{bmatrix} \qquad (2)$$

The zero elements in the fifth column and in the sixth row of eq. (1) occur because of time independence and conservation of energy in static magnetic fields. Introducing clystron bunchers as lenses for the longitudinal phase space leads to non zero values for all elements concerning the horizontal and longitudinal phase space (R_{ij} with i,j = 1, 2, 5, 6) in the general transformation matrix because the forces in the bunchers are time dependent and do change the energy of the particles. A beam with all these correlations would be very hard to deal with for the designer and especially the operator. This strong coupling between the horizontal and longitudinal phase planes can be greatly reduced if the planes are decoupled at the location of the bunchers. In connection with eq. (2) this is the condition $R_{16} = R_{26} = 0$. Under these circumstances the phase planes are decoupled at all locations where the magnetic system itself is achromatic. Otherwise at least the transformation elements R_{61} and R_{62} remain zero.

The dispersion introduced into the beam by the analyzing magnet of the Van de Graaff can be neglected since the energy spread of the beam at the exit of the pre-accelerator is about a factor of 10 less than the energy spread applied by the first buncher.

2. The achromatic condition must be fulfilled also at the stripper. One reason is that the small aperture of the gas channel does not allow a beam spreading by radial dispersion. The other reason is the considerable energy and angle straggling in the foil stripper which is of the same order of magnitude as the energy and angle spread in the beam before the stripper. The condition at that place is not only a sharp focus in all three dimensions in order to minimize the enlargement of phase space but also to have no correlations between the phase planes. Any correlations would be changed by the straggling irreversibly and the phase space effectively increased.

Telescopic optics. In the transformation matrices for the horizontal and vertical planes between s1 and str and between str and b2 the off-diagonal elements R_{12}, R_{21}, R_{34} and R_{43} are zero (besides $R_{16} = R_{26} = R_{51} = R_{52} = 0$). This is the condition for point to point as well as parallel to parallel imaging. As the latter is essential for telescopes in light optics such a property is called "telescopic imaging". The advantage over normal point to point imaging is that overfocusing effects are avoided. In addition each object waist is transformed into an image waist independent of the shape of the starting phase ellipses. The settings of the magnetic elements therefore are determined by only the magnetic rigidity of the beam.

The telescopic imaging is achieved making use of the focusing properties at the entrance and exit of the dipole magnets. The symmetry of the first achromat with respect to the middle of q_2 is extended and reaches from s1 to str. Telescopic optics in both planes can also be obtained for each half of that part of the system ($R_{12} = R_{21} = R_{34} = 0$ in the middle of q2; besides $R_{26} = 0$). The symmetry then leads to the unity matrix for the horizontal and vertical transformation between s1 and str. This reproduces the sharp focus at the analyzing slit s1 at the stripper. A change in the magnification between s1 and str can be obtained by means of the quadrupoles q_1 and q3 shifting the intermediate image inside the achromat towards slit s2 or s3 (see fig. 2). In that case the transformation between s1 and str remains nearly telescopic over a wide range of variation. The telescopic system between str and b2 has a fixed magnification of $R_{11} = R_{33} = 1.5$. In the horizontal direction there is a sharp intermediate image at slit s4 between dipole c and quadrupole q5 (see fig. 2).

Adapting to the cyclotron. At the entrance of the cyclotron eight parameters of the beam have to be matched to first order. These are two parameters for the phase planes in each of the three directions (e.g. the ratio of the axis of the phase ellipses and their orientation) and two values describing the correlation between the horizontal and longitudinal phase space (radial and angular dispersion).

The bending unit e-q8-f is constructed in a similar way as the two achromats. It brings the beam into the final direction for injection into the cyclotron. Besides that a proper (mainly angular-) dispersion at the exit of the unit is choosen by means of the setting of the quadrupole singlet q8. With the doublet q9 this dis-

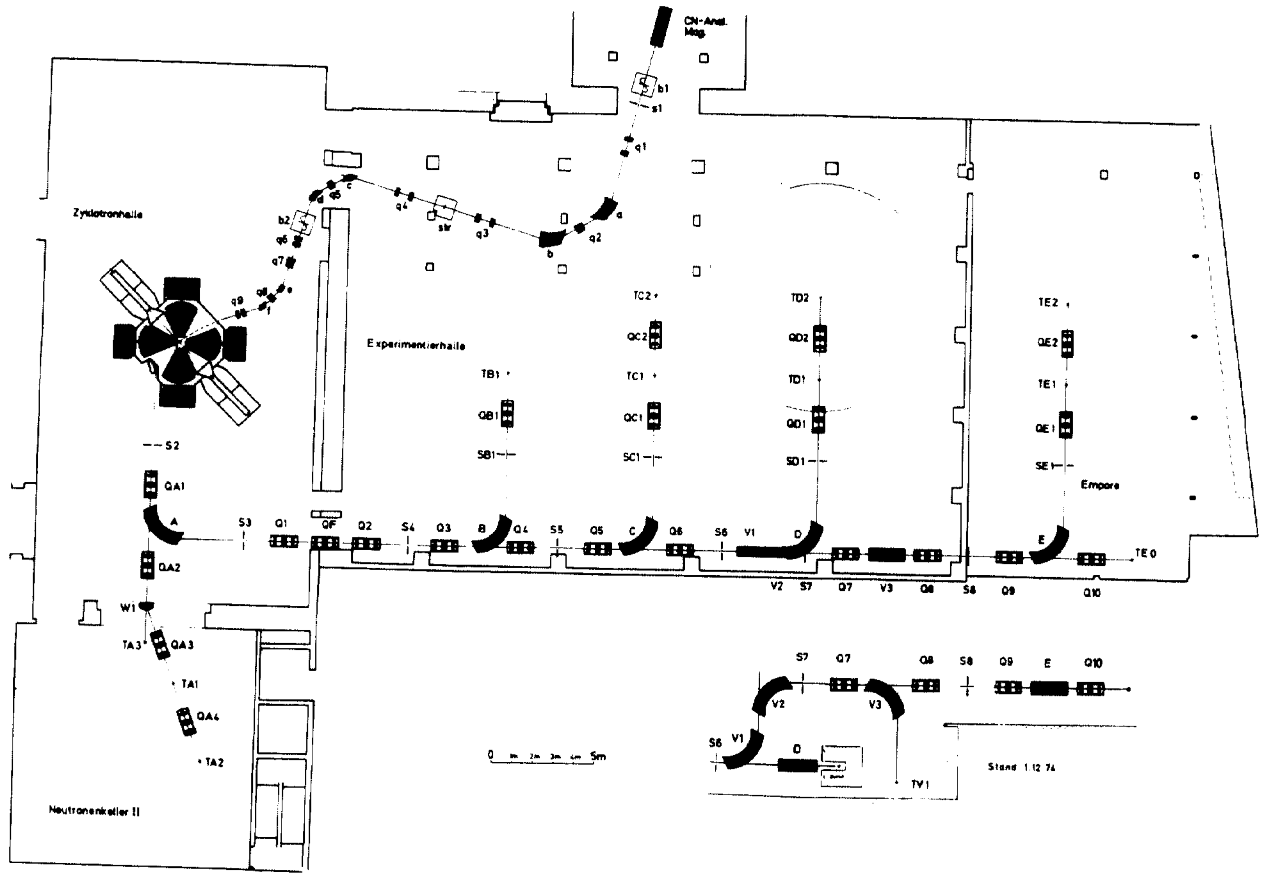

Fig. 1: Layout of the heavy ion accelerator combination VICKSI

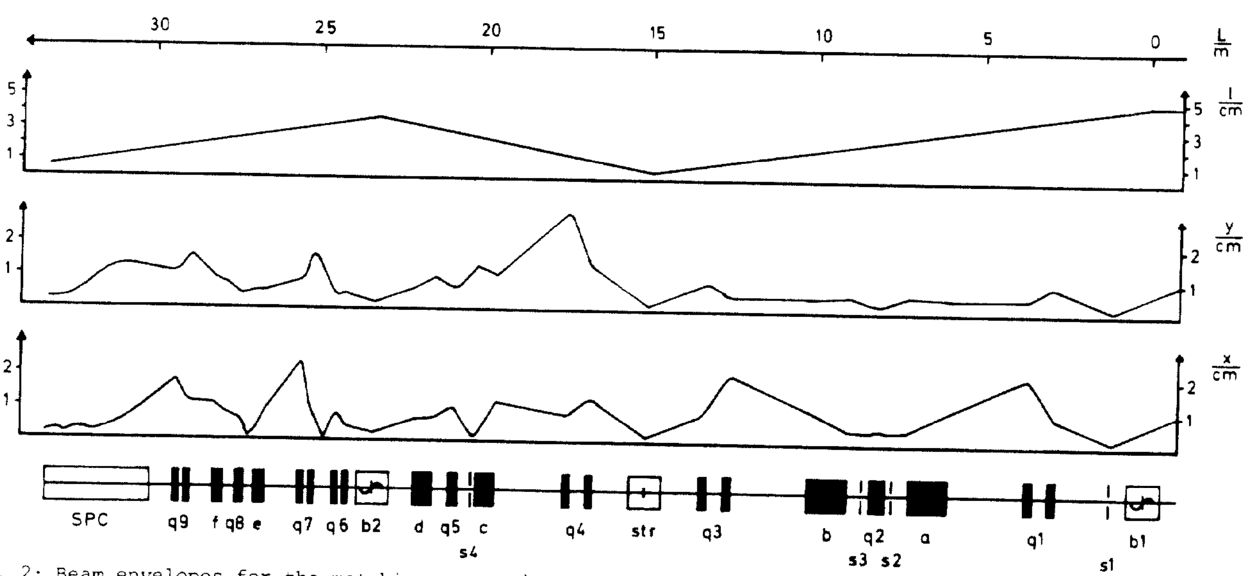

Fig. 2: Beam envelopes for the matching system between the two accelerators in the longitudinal, vertical, and horizontal direction. (Note that the beam moves from right to left.)

persion is transformed into the desired radial and angular dispersion. Calculating backwards gives at the entrance of the magnet e the form and orientation of the three decoupled phase ellipses. The longitudinal matching is done by the bunchers. For the horizontal and vertical direction the four gradients of the quadrupole doublets q6 and q7 are used to produce these phase ellipses.

The matching will be controlled by an emittance measuring system installed between q7 and e. A movable slit behind magnet f can determine the energy distribution of the beam. A simultaneous measurement of the time distribution of the ions passing this slit gives a pattern of the whole longitudinal phase plane.

Energy and phase selection

About 60 % of the particles out of the Van de Graaff are accepted within the linear part of the bunching system and transformed into the longitudinal acceptance of the cyclotron ($|\Delta E/E| \le 0.5\%$; $|\Delta\phi| \le 3^{\circ}$). The rest of the beam shows up as tails in the longitudinal phase space distribution, extending to $\pm 180^{\circ}$ phase deviation and up to ± 5 % energy deviation in the cyclotron. As there is a very strong correlation between energy and phase in those tails it is possible to select the phase by slits defining the energy.

There are two possibilities of energy and phase selection in the beam matching system namely in the dispersive regions inside the two achromats. The slits s2, s3 and s4 are foreseen for that purpose. In the first achromat either slit s2 or s3 may be used depending on the position of the intermediate image which is determined by the choice of the magnification between s1 and str. Using the slits in both achromats improves the energy resolution while maintaining the transmission. In addition the slit s4 is used for charge state selection.

The energy selection produces a gap between the desired and the unwanted phase space distribution. It can be achieved that in the cyclotron all unuseable ions deviate in phase by at least 90° and therefore are not accelerated but decelerated and easily removed after the first revolution.

Conclusions

The bunching system compresses 60 % of the DC-beam into a phase interval of 6° increasing the intensity in the pulse by a factor of 36. Therefore the specifications of other parts, like output of the ion source, can be reduced correspondingly keeping the same overall performance of the system. Alternatively the performance can be raised either directly in intensity or trading intensity for e.g. energy resolution or attainable energy. Using a less abundant higher charge state from the ion source or from the stripper extends the energy and mass range considerably.

The optimization of the beam properties at the stripper results in about 50 % increase for each of the three phase planes (horizontal, vertical, longitudinal) while factors of 10 can easily arise with less care. In our case this would lead to beam losses in the cyclotron. Furthermore for many experiments really the brilliance, the density of the beam in phase space, matters rather than the total intensity.

In spite of the apparent complexity it is rather straightforward to adjust the system since it is quite symmetric. More important is that the huge space of beam properties and adjustable parameters separates in independent, manageably small subspaces.

References

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