Summary

The Heidelberg 3MV heavy ion postaccelerator section based on independently phased normal conducting spiral resonators working at 108 MHz is described. The design velocity of the spiral resonators is \( \beta_0 = 0.10 \). The peak voltage drop is 0.37 MV at 20 kW CW input power (0.74 MV at 80 kW, duty factor 0.25) corresponding to a peak accelerating field of 1.17 MV/m (3.4 MV/m) averaged over the external length of the resonator. Using a synchronous phase of \( \phi = -20^\circ \) gives a maximum effective voltage of 0.35 MV (0.7 MV).

The resonators are stacked in modules of four with one external quadrupole doublet. The total effective voltage of this first test section of the Heidelberg postaccelerator under construction is 3 MV-CW (6 MV d.f. 0.25) providing ion energies up to 6 MeV/nucleon at mass A = 10. The postaccelerator will be integrated into the existing experimental area. Beam matching to the longitudinal acceptance of the postaccelerator is done by a separate spiral resonator as rebuncher. The high quality of the tandem beam with respect to longitudinal and transverse phase space is maintained in the designed postaccelerator.

I. Introduction

Normal conducting spiral resonators combine high shunt impedance and flexibility over a wide range of particle velocities with ease of fabrication and effective decoupling of electrical and mechanical properties from requirements imposed by the specific velocity profile of a linear heavy ion accelerator. This makes them very attractive as accelerating elements for postaccelerators behind existing electrostatic machines up to ion masses about of \( A = 100 \).

In early 1974 the development of a prototype accelerator based on independently phased spiral resonators was started. One complete prototype unit of such a linac consisting of the spiral resonator, the rf-generator and the regulation systems for frequency, phase and amplitude was developed (chapter II).

Successful longtime power and stability tests of this unit were followed by the construction of a 1 MV prototype module consisting of three spiral resonators and an external quadrupole doublet (chapter III). Beam tests with \( \alpha \) and \( \beta \) ions showed the feasibility of such a postaccelerator consisting of independently phased resonators. Based on this experience the construction of a first 3 MV test section of the Heidelberg postaccelerator was started in the end of 1975. The project has now left the stage of design and testing and entered the phase of realization.

II. The Prototype Unit

After a series of model measurements and optimizations of shunt impedance versus mechanical stability of differently formed spiral elements a power prototype was constructed. Extensive testing of coupling loops, tuning mechanisms and different spiral geometries resulted in the final form of the Heidelberg spiral resonator shown in fig. 1. The spiral element is formed from two \( 9.3 \times 9.3 \) mm\(^2\) Cu-profiles with a 7 mm diameter cooling channel silver soldered together in the radial plane. The drifttube at the free end of the spiral defines together with the grounded tubes at the endplates the two \( 20 \) mm acceleration gaps of the structure. The rf-power (25 kW at 108 MHz) is inductively coupled to the cavity by a tunable loop near the leg of the spiral. Thermal frequency shifts of typically 12 kHz/kW can be compensated by a servo operated tuning plate. The wide tuning range of 0.5 MHz also easily takes care of fabrication tolerances. Spiral, coupling loop, tuning plate and the 35 cm inner diameter tank are watercooled. A waterpressure of 8 kp/cm\(^2\) is sufficient for full power operation. A vacuum of better than \( 5 \times 10^{-7} \) Torr can be maintained under rf-power by a closed cycle cryopumping system.

The relevant data referencing the performance of the spiral resonators are given in table 1 for different design velocities \( \beta_0 = v_0 / c \).
Table 1 Characteristic parameters of selected spiral resonators (a = aperture radius of the drifttube)

<table>
<thead>
<tr>
<th>NO</th>
<th>( \beta_0 ) (mm)</th>
<th>( a )</th>
<th>( TTF_0 )</th>
<th>( R_p ) (20kW)</th>
<th>( U_t ) (MV)</th>
<th>( U_{T_{eff}} ) (20kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>24</td>
<td>0.06</td>
<td>10</td>
<td>0.94</td>
<td>2.99</td>
<td>0.35</td>
<td>0.32</td>
</tr>
<tr>
<td>6</td>
<td>0.06</td>
<td>15</td>
<td>0.90</td>
<td>2.62</td>
<td>0.32</td>
<td>0.29</td>
</tr>
<tr>
<td>20</td>
<td>0.10</td>
<td>10</td>
<td>0.98</td>
<td>3.34</td>
<td>0.37</td>
<td>0.36</td>
</tr>
</tbody>
</table>

\[
R_p = \frac{U_t^2}{2N_0} = \frac{(2U_D)^2}{2N_0}
\]

\[
U_{T_{eff}} = U_t \cdot TTF
\]

\[
TTF = \frac{I_0(2\pi/\beta)}{I_0(2\pi/\beta_0)} \cdot \frac{\sin \left( \frac{\pi}{\beta_0} (g + 0.85r_1) \right)}{\sin \left( \frac{\pi}{\beta} (g + 0.85r_1) \right)} \cdot P(\phi)
\]

\[
P(\phi) = \frac{1}{2} \left[ \cos \phi - \cos \left( \frac{\pi}{\beta} (g + 0.85r_1) \right) \right]
\]

The energy gain in phase focussing linac operation is given by

\[
\Delta E = \zeta \cdot U_t \cdot TTF \cdot \cos \phi_0
\]

with \( \zeta = \) charge and \( \phi_0 = \) synchronous phase

The optimum phase \( \phi_{opt} \) and the corresponding transittime factor \( TTF_0 \) for a spiral resonator with design \( \beta_0 = 0.10 \) to show the flat dependence on \( \beta \) in the range of interest. The values \( U_{T_{eff}} \) of table 1 are calculated with the transittime factor \( TTF_0 \) for the design \( \beta = \beta_0 \). With these values for \( U_{T_{eff}} \) the axial accelerating field averaged over the external length of one resonator is 1.8 MV/m for \( \beta_0 = 0.06 \) and 1.7 MV/m for \( \beta_0 = 0.10 \).

Fig. 2 Transittime factor and optimum phase for a spiral resonator with design velocity \( \beta_0 = \frac{v_0}{c} = 0.10 \)

Three different regulation systems are used: a frequency regulation operating the tuning plate, an amplitude control to keep the accelerating field constant to within 1% and a stabilisation loop to control the rf-phase between resonator-field and reference voltage to better than 10°.

More than 3100 hours of prototype tests with resonator input power of 19-23 kW-CW showed that these requirements for the operation of the linear accelerator can very well be satisfied.

III The 1 MV Prototype Module

In order to investigate the performance of a number of independently phased spiral resonators with a beam of heavy ions, an accelerator module consisting of three resonators and an external quadrupole doublet was built. Design values \( \beta \) of the resonators are 0.10, 0.06, 0.06. Fig. 3 shows this functional subgroup of the postaccelerator at the Max-Planck-Institut in Heidelberg.

Fig. 3 Postaccelerator prototype module with three spiral resonators, quadrupole doublet and analyzing magnet during assembly.
The electrical and mechanical dimensions of the resonators are those proved optimum during the tests of the prototype resonator. The only changes are the endplates simultaneously used by two resonators. In a power test of the module before the actual beam test the following stability could be demonstrated:

(i) longtime phase stability (>12h) &Delta;&alpha; < 0.5°
(ii) longtime amplitude stability (>12h) &Delta;U/U < 5x10^-3

During several acceleration tests DC beams of 32S and 58Ni ions were injected into the accelerator module after stripping to higher charge states in an additional stripper. The outgoing particles were focussed by the quadrupole doublet onto the 1mm analyzing slits of a 35° deflection magnet. Fig. 4 shows the maximum energy modulation of a DC 140 MeV 58Ni beams that was obtained after optimization of the relative phases of the resonators. As the particles of the DC beam are entering the module at random rf-phases maximum acceleration and deceleration occurs at the R-values labeled R_H and R_L.

![Measurement of Energy Gain](image)

**Fig. 4** Momentum distribution of postaccelerated 140 MeV 58Ni ions measured with a 35° analyzing magnet.

The different heights of the peaks at minimum and maximum energy are due to phase oscillations.

At a total CW input power of 61 kW an energy increase of &Delta;E = 18.4 MeV was obtained. This corresponds to an effective voltage drop of U_eff = 0.68 MV, a value which agrees reasonably with the calculated one from Table 3. The effective accelerating field E_eff = U_eff/L averaged over the external length of the module is 1.55 MV/m in this experiment. The design velocities of the resonators in the module were different from the velocity of the injected ions (0=0.076). Therefore the transittance factor was reduced in all three cases.

<table>
<thead>
<tr>
<th>No</th>
<th>R_p (mm)</th>
<th>R_T (mm)</th>
<th>F (kW)</th>
<th>P_l (MV)</th>
<th>U_eff (MV)</th>
<th>U_C (MV)</th>
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<tbody>
<tr>
<td>24</td>
<td>0.06</td>
<td>0.92</td>
<td>2.99</td>
<td>20</td>
<td>0.32</td>
<td>0.68</td>
</tr>
<tr>
<td>17</td>
<td>0.06</td>
<td>0.92</td>
<td>3.23</td>
<td>20.6</td>
<td>0.34</td>
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<tr>
<td>20</td>
<td>0.10</td>
<td>0.78</td>
<td>3.34</td>
<td>20.6</td>
<td>0.29</td>
<td></td>
</tr>
</tbody>
</table>

**Table 2** Characteristic parameters of the 1 MV module during acceleration test (a = aperture radius of the drifttube)

## IV The 3 MV Postaccelerator Section

Based on the successful tests of the 1 MV module a first section of the Heidelberg postaccelerator is under construction. Its total effective voltage will be 3MV-CW (6MV, duty factor 0.25). The energies per nucleon that can be obtained for different masses of poststripped ions are depicted in fig. 5.

The shaded area at the top of fig. 5 gives the ion energies that would be provided if the postaccelerator is expanded to 30 resonators. Such an extension is easily possible because of the modular character of the system.
The physical layout of the 3 MV section and the beam transport system is shown in fig. 6. The beam transport system has been specially designed to fit the postaccelerator into the building of the MP-tandem and to bring the postaccelerated beam to the existing experimental area already in a very early stage of installation. The layout allows for the extension of the postaccelerator by a simple insertion of additional resonators.

The beam coming from the MP-tandem is displaced parallel by two 60° dipoles and a quadrupole triplet. After passing the postaccelerator the beam is brought back to the MP beam axis by two 90° deflections which are accomplished by one 90° - and a combination of 20° and 25° dipoles providing beam lines to new target areas. The MP-analyzing magnet will be placed on a turntable to serve alternatively the existing target areas with the direct beam from the MP-tandem or with the postaccelerated beam without changing the optical mode of the existing beam transport system.

In detail the pulsed beam is focussed through the high energy chopper and the first 60° dipole through horizontal (stabilization of the MP-tandem) and vertical (stabilization of the nanosecond beam pulsing system) slits. This double focus is imaged on the stripper II by a quadrupole triplet. Thus the magnet system minimizes the influence on the emittance of small angle scattering from the stripper. This system is achromatic and therefore preserves the time structure of the pulsed beam.

The matching of the beam to the longitudinal and transversal acceptance of the linear accelerator is done by the rebuncher and the following quadrupole triplet respectively. The high quality of the tandem beam with respect to energy resolution is restored by a debuncher spiral resonator which can alternatively be used to achieve good time resolution in connection with a further rebuncher.

The design of the 3 MV section is similar to that of the 1 MV prototype module already tested. The design velocity of the spiral resonators is \( \beta = 0.10 \). The voltage drop is 0.3 MV with 20kW-CW input power (0.6 MW at 80 kW, duty factor 0.25) at a synchronous phase of \( \phi_s = -20^\circ \).

The resonators will be stacked in modules of four with one external quadrupole doublet (field gradient 3 kG/cm, aperture 45 mm, length per singlet 15cm).

This configuration has been found to be optimum with respect to acceptance, preservation of the tandem beam quality and total length of the machine by extensive beam dynamic calculations. The acceptance of the postaccelerator is about 7cm mr for a 2cm diameter drifttube aperture. The calculations have been performed with modified GSI beam dynamic codes and include the nonlinear coupling between transverse and longitudinal phase space. They showed that a transverse emittance of \( \epsilon_x = \epsilon_y = x' x'' = 0.8 \text{ cm mr} \), which represents an upper limit of the MP-tandem emittance, is not deteriorated by the booster. The same holds for the longitudinal emittance of \( \epsilon_L = \Delta W \cdot \Delta \phi = 3.5^\circ \text{ MeV} \) if the beam is rebunched to \( \Delta x = 7^\circ \Delta \phi = 20^\circ \text{ps} \). The value of \( \epsilon_L \) is consistent with measurements behind the existing ns-pulsing system and represents about 20% of the DC beam intensity. As the limit for phase jitter were obtained. The alignment tolerances of the quadrupoles are \( \pm 0.1 \text{ mm} \) and \( \pm 10 \text{ mr} \). This accuracy introduces no problems since the quadrupoles are separate from the structure and easily accessible.

The rf generators and the regulation system are essentially the same as those used for the 1 MV test-module. The rf transmitters as well as the electronics will be modified for pulsed operation. The beam
transport system and the linac will be computer-controlled by a PDP11/34. All components of the complete system are constructed to be CAMAC compatible. A microprocessor crate controller will serve as back-up system for manual control.

The status of the project (in early March 77) is as follows:
The testing of the prototyp components like spiral elements, coupling loops, tuning plates and the electronic systems is finished. Series production of these elements has started. The rf-transmitters and the complete beam transport system have been delivered, the cryopumps are ordered. Construction of the vacuum system has started. The conceptual design of the computer control system is finished, the development of software has been started. The construction of an accelerator vault inside the experimental hall for radiation shielding, and the installation of the power and cooling system has begun.

V. Conclusion

After a test phase that will begin in the end of 1977 and the completion of the beam transport system in the beginning of 1978 postaccelerated heavy ions up to 6 MeV/nucleon at mass A = 40 will be available at the existing experimental area in Heidelberg.

References

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Acknowledgement

The authors are indebted to Professor Peter Bräux for encouragement and support during all phases of the project. They gratefully acknowledge the skilful and enthusiastic work of many technicians of the Max-Planck-Institut für Kernphysik.