OPERATION OF THE HEIDELBERG HEAVY-ION POSTACCELERATOR

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Summary

The 3MV-stage of the Heidelberg Heavy-Ion Postaccelerator went into operation in December 1977, and is in the state of full user availability since May of 1978. The machine uses spiral resonators at room temperature. Ten such resonators with design velocity β_o = 0.10 at 108.48 MHz are operated either CW at 20 kW or in a pulsed mode (DF = 0.25) at 80 kW. Due to the flexibility of the independent phasing of the 10 resonators presently in operation, a wide variety of ions between ^{12}C and ^{79}Br have been accelerated for user experiments. Acceleration voltages as high as 3.3 MV (CW) and 5.5 MV (Pulsed Mode) could be demonstrated.

An energy resolution of $\Delta E/E < 4 \times 10^{-4}$ allowing rebunched pulse widths of $\Delta t_{FWHM} < 70$ ps could be measured, showing the tandem-like beam quality. The machine is exclusively computer-controlled, a prerequisite for the operation of the many parameters of a tandem-postaccelerator-combination. The overall availability of the postaccelerator together with the MP Tandem was above 80% of the scheduled user beam time. The operation of the 3-MV stage is now interrupted for a 4-month shutdown till the end of 1979, to allow for the extension of the machine to its full 10 MV (CW) acceleration voltage by the addition of 20 more spiral resonators.

The Spiral Resonator - Postaccelerator

Development, construction and prototype tests of the normal conducting spiral resonator of the Heidelberg-type have been described in Refs. 1 and 2. Figure 1 shows a cut drawing of the structure to summarize the main features of this type of resonator. The dominant element in the figure,

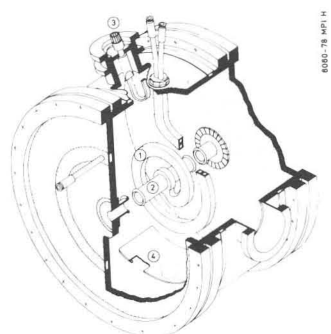

Fig. 1
Cut drawing of the Heidelberg spiral resonator. Tank inner diameter is 35 cm.

labeled (1), is a $\lambda/4$ line resonator wound as a spiral. The leg of the spiral is screwed to the outer shell of the resonator, while the free end, the location of the voltage maximum, holds the drift tube (2) between the two grounded tubes forming the accelerating gaps. Gap width and drift tube bore are 2 cm each; gap-to-gap distance is $\ell = \beta_o\lambda/2$. Thus the structure has a very wideband transit time factor necessary for the desired high flexibility to accelerate ions of very different initial velocities and charge-to-mass ratios from the MP-Tandem. The rf power is coupled to the resonators by a turnable inductive loop (3) extending into the resonator near the leg of the spiral. The resonance frequency is maintained by a servo loop controlled capacitive tuning plate (4). Characteristic parameters of the resonators are listed in Table I.

Table I. Parameters of the spiral resonators used in the 3 MV-stage of the Heidelberg Postaccelerator

Operating frequency (MHz)	108.48
Quality factor Q	3500
Design velocity β_o	0.10
Shuntimpedance Z (MΩ/m)	30
Input power N_{cw} (kW)	20
N_p (kW (25% duty cycle)	80
Effective voltage (ϕ_s =-20°)	
U_{cw} (MV)	0.33
U_p (MV)	0.60

Figure 2 is a drawing of a postaccelerator module stacking four spiral resonators. Two resonators always share one common flange carrying the grounded drift tubes. One operational module yields a total effective voltage of 1.3 MV (CW) at a synchronous phase ϕ_s = 20°. Each set of four spiral resonators has an external quadrupole doublet with a maximum field gradient of 3 kG/cm, 45 mm aperture and 15 cm length per singlet. A

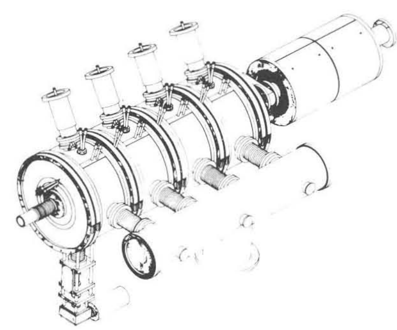

Fig.2 Accelerator module consisting of four spiral resonators, quadrupole doublet and pumping line.

vacuum better than 1×10^{-7} mbar is maintained by a cryopump (2 W, 20 K closed-cycle refrigerator) with an external pumping line arrangement. The characteristic beam dynamics parameters of such a setup have been discussed in[1,3].

For the first 3 MV-stage of the Heidelberg booster three accelerator modules were manufactured in the Institute's main workshop in 1977.

The accelerator layout and beam transport system have been designed to fit the postaccelerator into the present MP-Tandem accelerator building and to bring the postaccelerated beam back to the existing experimental area. Details can be found in Ref.3. Figure 3 shows a photograph of the linac and the beam transport system.

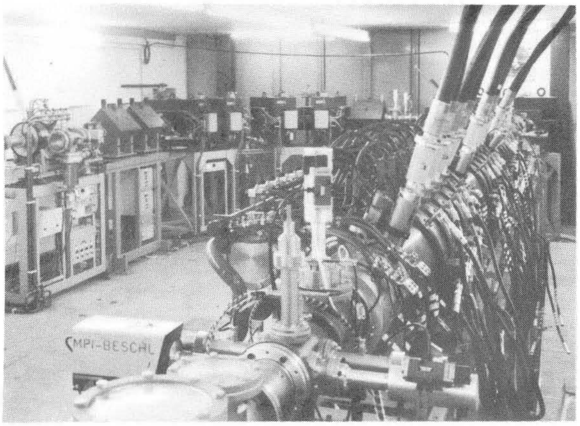

Fig.3 View of the 3-MV-stage of the Heidelberg Postaccelerator. Three modules with β_0=0.10 - spiral resonators are seen at the right side, followed by part of the beam transport system and debuncher (to the left). See Ref. 3.

Rf Generators and Control Electronics.

In the first 3-MV-stage of the booster, 12 commercially available FM broadcast transmitters with an output power of 20 kW CW are used to feed the cavities. They are of the same type operated in the power and beam test in the years 1975-76, and have proven to be reliable and rugged. For use as the rf supply of the linac they had, however, to be modified considerably to meet the requirements of the computer-control as well as to operate them from one common anode power supply and to run them in pulsed mode. Figure 4 shows a view into one row of the transmitter gallery. The generators are set up in groups of four, one group belonging to one accelerator module. The 19" racks in the background house the driver amplifiers, the reference signal distribution, the regulation units for phase, amplitude and resonance frequency and the phase shifters necessary for each individual cavity as well as a CAMAC crate of the computer-control. All the regulation units have been designed and manufactured in-house.

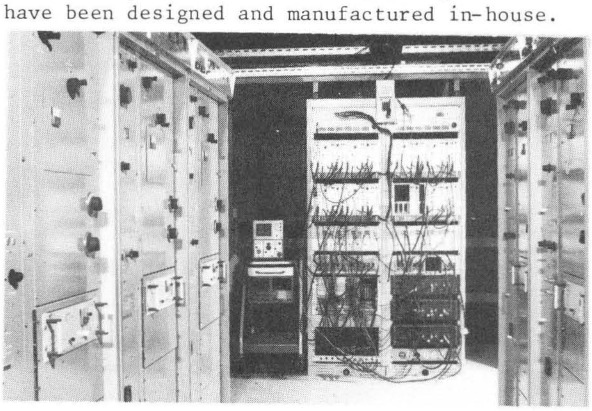

Fig. 4 View of the rf gallery showing transmitters and regulation and control systems.

The Computer-Control System

The use of independently phased resonators for acceleration of a large variety of different ion species delivered by the electrostatic tandem injector, demands efficient computer assistance of the operator. A computer program to calculate all settings for rf amplitudes, phases, quadrupole gradients and dipole fields which depend strongly on the injection parameters, was mandatory. Control of all parameters directly by a computer maintaining the accessability for manual interaction was highly desirable.

The concept of the computer-control (see Ref.4) was based on the following general guidelines in order to limit the complexity of the overall system:

a) all remote control of the postaccelerator should be performed only via the computer. As no hardwired back-up system for control was to be installed, this decision enormously simplified the wiring as well as the logic of the programming, but demanded a reliable and comfortable interface between the operator and the accelerator hardware.

b) The computer-control system should not be used for closed-loop regulation of parameters or for operating safety interlocks. Every critical device should have its own hardware regulation system keeping track of the values set by the computer and should be protected by its own hardware interlocks which should react even in the case of a computer failure. Similarly, the computer should not have to synchronize with the accelerator to acquire time-dependent parameters. All rapidly varying parameters, e.g., in the pulsed operation mode, have to be latched to be read at any time. By these provisions, timing problems were greatly alleviated.

c) The control system should reflect the modularity and expandability, which are the key features of the accelerator itself. Thus, the inclusion of additional parameters, controls or functions as well as the expansion of the overall system by a factor of three, should be easily possible without major modifications to the existing system.

d) As most of the rf regulation electronics had to be designed and built in-house, the control system had to be based on standard, commercially available products to the widest possible extent. Thus, the CAMAC standard was adopted for the control system of the Heidelberg postaccelerator.

The Control Hardware

The accelerator control hardware is schematically indicated in Fig.5. The system is controlled by a dedicated PDP 11/34 minicomputer equipped with 128k of memory, a floating point processor and standard peripherals facilitating the development of the software.

All accelerator components and the operator's console are accessed via a single JY 411-CAMAC interface, which can directly drive a parallel CAMAC branch as well as a serial high-

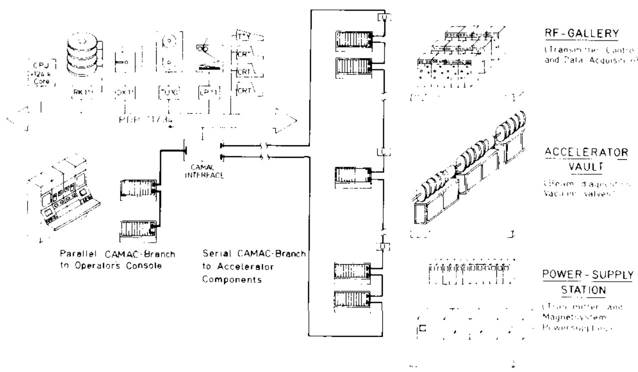

Fig.5 Schematic diagram of the Heidelberg postaccelerator control system.

way. Both branches are completely compatible with respect to software as they use the same control registers, and all features like direct memory access from CAMAC into the memory, or vice versa, are implemented for both branches. The high speed parallel branch is used for servicing the operator's console where various display units need to be updated rapidly. Though refresh rates between 1 Hz and 10 Hz depending on the type of unit, have proven to be sufficient, much care was taken to minimize the response to an operator's intervention. The serial highway runs as a large loop of about 300 m total length from the computer through three floors of a remote part of the building. Only one cable, consisting of 9 twisted pairs necessary for a byte-parallel serial highway, interconnects the different hardware components of the accelerator and essentially is the only link for communication between the operator and the postaccelerator. Basically, four standard types of highly integrated CAMAC modules are used throughout the accelerator, keeping the number of crates down to a minimum. Readout of analog values is achieved by an ADC module with 32 independent differential input channels. Setting of analogue values by the computer is performed by 12-channel DAC modules. A specially designed transmitter-control module combines 24 relay contacts and 24 status flags for a completely remote operation of one 20-kW rf station. A fourth type of module is used for the control of one magnet power supply each. In addition to these four basic modules there are relay multiplexers, which are used to select analog signals for inspection at the console for diagnostic purposes.

Though these modules are quite different in function they all meet one common criterion which has proven to be essential for easy software development: to perform a specific operation the computer needs to know and execute only one single CAMAC command and not a series of consecutive steps. Thus, formally, all units can be handled identically and no special device drivers are necessary.

Software Organization

The PDP 11/34 is operated fully under control of the multitasking operating system RSX-11M. The control software is largely subdivided into different smaller programs which are responsible for specific operations and can be run independently from each other in parallel. By this scheme the software development and maintainance was greatly facilitated. Tasks which have to perform larger numerical calculations are written in FORTRAN, whereas the control software is written in assembler language.

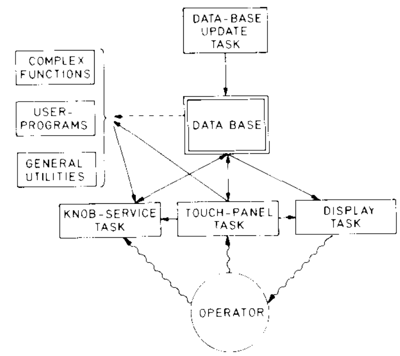

Fig. 6 Structure of the control software

Figure 6 shows the structure of the main software. The main effort was invested into the scheme of a data base which contains all information on the accelerator components, e.g. CAMAC addresses and commands, actual values, calibration factors and the names of the parameters. This data base is stored in the memory. Using a memory-resident data base guarantees fast access and fast response.

All tasks can access the CAMAC hardware only by using the information stored in the central data base. After changes or additions to the hardware, in most cases, just the data base needs to be updated. Without further programming the basic control routines will then have access to the newly installed components.

Three primary control routines are provided which together with their related hardware components at the console are completely equivalent to a conventional operator's console and enable the operator to perform all necessary operations manually. These are
i) a display routine, to inspect all required parameters on a TV-screen; ii) a knob service routine to change or optimize settings of parameters manually; and iii) a touch panel service routine as the central program.

By touch panel interaction, the operator has full access to the data base. At maximum, four logically consecutive steps are required to uniquely specify a parameter, which afterwards, by touch panel command, can be included in the display table or connected to one of four control knobs. Simple functions, like switching operations, are directly performed via the touch panel. For convenience, there are preformatted pages of parameter sets which can be called for display.

Without appreciable difference the operator can perform more complex operations like the startup sequence for one rf generator or even the whole accelerator. For such purposes there now exist a large number of different tasks which can be started via the touch-panel and which communicate with each other under control of the operating system.

Initial setting of the postaccelerator components is achieved by an interactive optimization routine which from basic information on the injected beam parameters optimizes the linac parameters for a requested output energy with respect to the beam acceptance. All focusing and beam handling elements as well as the rf amplitudes and phases are set to the calculated values directly by that program. Only minor manual fine tuning and optimization with respect to beam transmission for the injection and extraction region is required afterwards, whereas the linac settings can remain unchanged.

The control console of the postaccelerator consisting of two equivalent stations is shown in Fig. 7. The center part is the touch panel, a CRT display just above, and four control knobs below. The control knobs are simple, two-speed pulse-generators which feed a presetable up-down counter. For each knob the actual assignment and the current value of the parameter can be read on a small alphanumeric display. Other beam diagnostic elements like beam profile monitors, fluorescent screens or slits are operated similarly, a normal TV-monitor and a small oscilloscope being used for display purposes. For diagnostics the rf signals from resonators or transmitters can be selected for display on the larger oscilloscope.

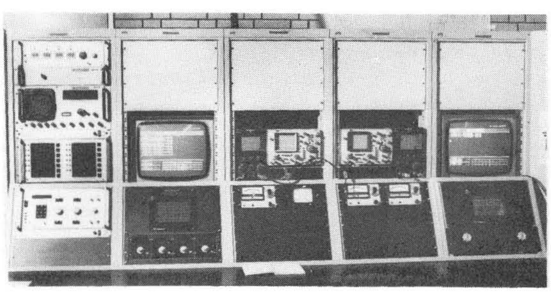

Fig. 7 Operator's console

This scheme of control system has been readily accepted by the operators, as it does not require any knowledge of computer hardware or software. The use of typical computer peripherals like keyboards for control purposes has been almost completely avoided.

As all parameters have their names in plain language with minimal use of abbreviations the operation of the touch panel has become transparent and straightforward even for untrained personnel.

IV. Operation Experience with the Postaccelerator

The Heidelberg postaccelerator started test operation in December 1977, and is in the state of full user available operation since May of 1978. By the end of July 1979, 17 user beamtimes could be operated. Altogether 1498 hours of user time had been scheduled from which for 1223 hours of useful beam were provided for the experiment. These figures correspond to an overall availability of the combination MP-Tandem postaccelerator of 82%. Table II summarizes characteristic data of selected postaccelerated heavy-ion beams as typical examples of the machine performace. The table shows

Table II

Ion	q_{NB}	E_{MP} (MeV)	E_{PA} (MeV)	U_{eff} (MV)	I_{el} (nA)	$\Delta E/E$ (10^{-3})	ε_r (π mm, mrad)
^{12}C	6+	72	90	3.03	100	<4.3	--
^{32}S	14+	132	178	3.30	85	<5	3.1
	15+	132	181	3.28	30	--	4.2
	14+	108	152	3.15	50	~0.4	2.9 [1]
	12+	140	178	3.13	40	<1	2.8 [2]
	13+	150	190	3.11	15	-	-
^{32}S	12+	140	206	5.52	30	-	- [3]
^{58}Ni	16+	177	225	3.01	30	-	3.22 [2]
^{79}Br	16+	177	246	4.31	10	-	- [3]

1) (140 ps→300 ps), 2) User Run, 3) 65 kW)

that ions between ^{12}C and ^{79}Br can be accelerated by the present 10 resonators with almost equal effective voltage, (column 5), which is in all cases above 3 MV. The measured energy resolution of less than 5×10^{-3} (column 7), in some cases well below 1×10^{-3}, will be improved by one order of magnitude with the debuncher. The radial emittance ε_r is smaller than the projected value of 5π mm - mrad indicating that the postaccelerator is longitudinally and transversally properly matched to the tandem beam. Row 7 shows an example of the machine performance in pulsed mode. Running the cavities with a peak power input of 65 kW (1:4) resulted in an effective voltage gain of 5.52 MV. In the setting shown in row 4 a ^{32}S beam was gas stripped in the MP to a charge state of 8+ and further foil stripped before the booster to 14+. The final energy was 152.1 MV. Measured at the linac exit and 50 m downstream, the time halfwidth of the micropulse had only increased from 140 ps to 300 ps. From this an energy spread of $\Delta E/E \sim 4 \times 10^{-4}$ can be deduced. Beams of this quality have been rebunched in user runs to pulse widths of less than 70 ps[2].

V. Status of the Further Extension

The status of the extension of the machine to its final 10 MV acceleration voltage in early September 1979, is as follows: The fabrication of the additional five modules (3 modules $\beta_o = 0.06$, 2 modules $\beta_o = 0.08$) already started in August 1978, in the Institute's workshop. Since July 1979, this new part of the Linac is assembled, vacuum tested and prealigned, ready to be moved to its final location. Rf generators, regulation electronics and the additional CAMAC modules are in-house. The extension of the computer control system has been completed. A four-month shutdown of the postaccelerator began in early September 1979; operation is scheduled to start again at the end of this year. Normal MP-Tandem operation will not be affected.

Acknowledgement

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