Status of the VICKSI Project

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Abstract

The heavy ion accelerator combination VICKSI being built at the Hahn-Meitner-Institut in Berlin consists of a 6 MV single stage van de Graaff accelerator injecting into a 4 sector split pole cyclotron with a mass energy product of K=120. The primary design aim for this accelerator system is to reach 200 MeV for Carbon to Argon ions. The original HVEC Model CN Van de Graaff including the high voltage terminal with ion source is undergoing major reconstruction to achieve the necessary heavy ion performance. All parts of the beam matching system between the two accelerators have been ordered including the stripper and the two bunchers. The cyclotron is built by Scanditronix/Sweden. Three main magnets are completely assembled at the factory for field mapping. Mounting of the first RF-system will be finished around October. Installation of the cyclotron in Berlin is scheduled for 1976 and first trials with beam are anticipated for February 77. The new building for the cyclotron including power- and cooling installation will be ready in 75. Most of the electronics for the computer control of the complete system are delivered. The beam handling between the cyclotron and the target has been designed in detail.

Introduction

In fall 1971 the Nuclear Physics Division of the Hahn-Meitner-Institut Berlin proposed the VICKSI accelerator combination as its new central facility for the about equally split research activities in nuclear physics, nuclear solid state physics, and atomic physics [1]. This scientific program asked for a multiparticle variable energy machine with good and flexible beam properties and possibilities for future improvements. The VICKSI combination will fulfill these requirements making full use of the existing Van de Graaff and experimental hall. The anticipated beam data are summarized in table 1. The project was finally approved in April 73. Also the contract for the entire cyclotron construction from design to running in was signed then. Everything else which amounts to half of the

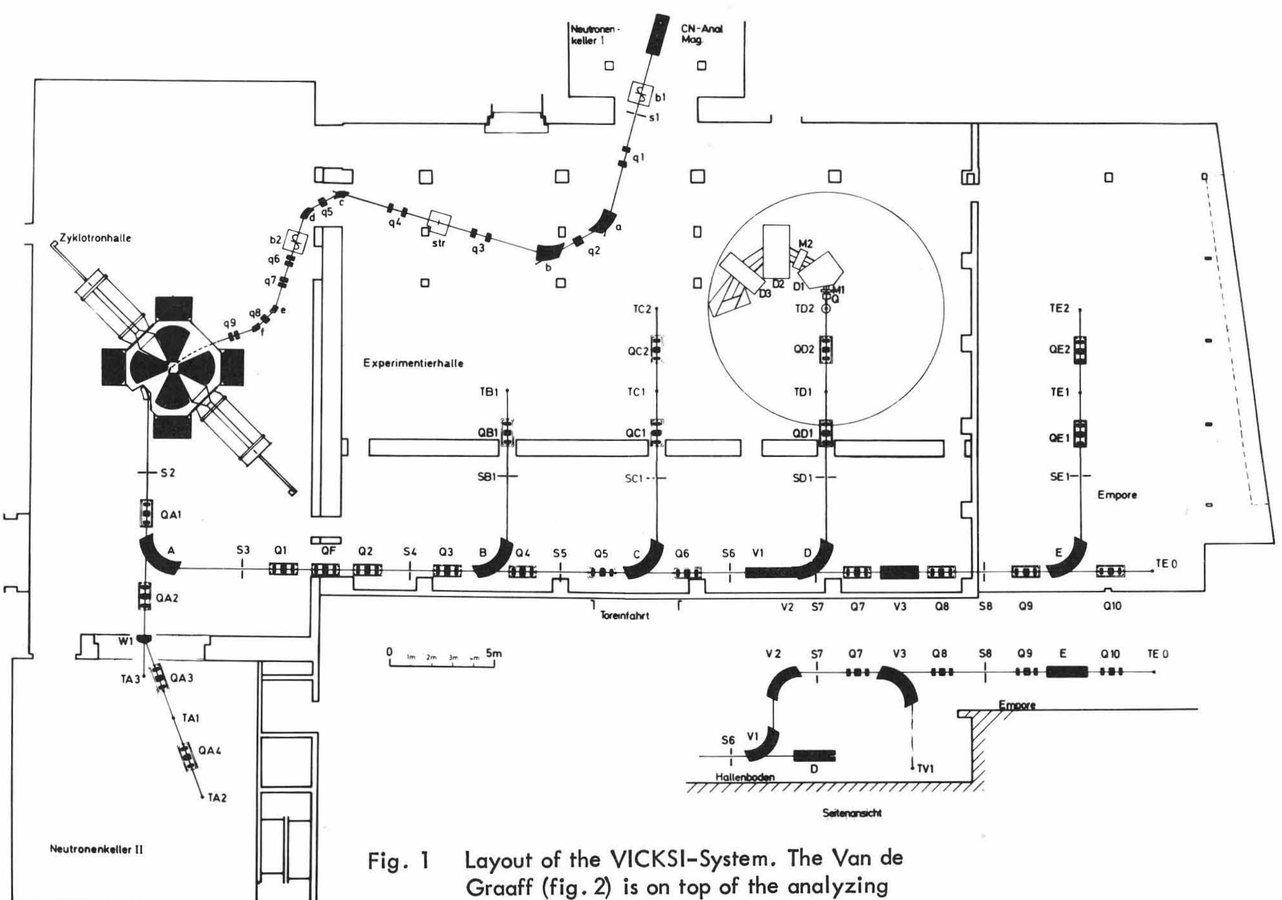

Fig. 1 Layout of the VICKSI-System. The Van de Graaff (fig. 2) is on top of the analyzing magnet (center top).

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project is handled by HMI itself. This report covers the progress since the Vancouver conference in 72 where we presented the proposal [2]. More information on some aspects can be found in other general reports [3-6].

Mass range	$1 \lesssim A \lesssim 40$ (80)
Energy limits (1)	$E \lesssim q$(ion source) · 100 MV
Energy limits (2)	$E \lesssim 120\, q^2$ (stripper)/A
	$E_p = 50$ MeV, $E_d = 60$ MeV,
	$E(^3He) = 160$ MeV, $E_\alpha = 120$ MeV
	E = 200 MeV
Primary goal: ($12 \lesssim A \lesssim 40$)	$E/\Delta E = 1000$
	I = 100 pnA
	emittance 5 mm mrad
	pulse width $\lesssim 1$ ns

Table 1: Main specifications of the VICKSI system

General concept

In the terminal of the Van de Graaff multiply charged heavy ions are produced. The ions are prebunched, mass analyzed and then accelerated by 6 MV in the Van de Graaff to q_i · 6 MV. The beam matching system to the cyclotron comprises a stripper to increase the charge state to q_s and two bunchers to achieve a phase width of 6^o. The cyclotron is of the split pole type with 4 separated magnets with a mass energy product K = 120 MeV. Injection proceeds in midplane through a nearly field free valley. The energy gain in the cyclotron is a factor 17. From this the two energy constraints of table 1 follow. Only for protons there is an additional limit at $E_p \simeq 50$ MeV.

At first the aim is to accelerate 2^+ ions in the Van de Graaff giving 200 MeV final energy. For $A \lesssim 25$ then the most abundant charge state from a gas stripper and for $A \lesssim 50$ that of a foil stripper can be used without violating the second requirement. If one uses less abundant charge states the following energies can be reached (table 2) with the stripper cyclotron combination (limit 2).

Yield of charge state q_s	Stripper medium	E_{max} in MeV Ne	Ar
>10 %	foil	490	360
	gas	380	75
> 1 %	foil	600	590
	gas	490	240

Table 2: Possible energies from the stripper-cyclotron combination.

With the present ion source however the intensity will also go down roughly a factor of ten per charge for the then required higher charge states q_i from the source (limit 1). With improved sources or another injector these energies can become feasible in the future.

At 200 MeV and below the first goal is to achieve 100 pnA extracted beam with 10^{-3} energy resolution. Theoretically only a factor of 3 in intensity is lost at the stripper and a factor 2 by converting the dc-beam from the ion source into a pulsed beam. At least for the present source output with noble gases this leaves a factor 10 safety margin. For singly charged ions from the source currents can be much higher and for light ions (p,d,^{3}He,α) radiation safety is the limiting factor at around 1 μA.

The beam handling behind the cyclotron provides 10 target positions with flexible preparation modes for high energy resolution $E/\Delta E$ = 5-10 000, sharp pulses (<1 ns) and special other experimental requirements.

Van de Graaff Injector

The Van de Graaff has been equipped with a bakeable all metal-ceramics tube from NEC to achieve the vacuum required for heavy ion acceleration. A pressure below $5 \cdot 10^{-9}$ torr has been achieved close to ion getter pumps at both ends of the tube. At the moment a preliminary heavy ion terminal is installed for beam tests. It includes the final Penning source and a specially developed turbo-molecular and a forepump that take the bulk of the gasload from the source and stand the 15 atm pressure from the insulation gas. When running beam, the pressure at the entrance of the acceleration tube where also an ion getter pump is situated is about 10^{-7} torr and at the exit 10^{-8} torr. As a consequence no Bremsstrahlung or other beamloading effects could be detected when accelerating 7 μA of Neon at 4 MV. This present voltage limit is due to the provisional corona type voltage divider along the tube which will be exchanged. Without beam the tube held 6 MV as far as tests were feasible with this voltage divider. It therefore seems safe now that 10 pμA can be accelerated at 6 MV and the danger of radiation damage to the terminal electronics is small. The fast gas handling system with a turn around time for access to the terminal of 3 h is in routine operation. The next steps will be to install the new enlarged spinning (electrostatic cover of the terminal) which makes room for the final terminal and reduces the maximum field strength at the surface from 25 MV/m at 7 MV terminal voltage to 20 MV/m. Installation of the final terminal is scheduled for spring 76. Fig. 2 schematically shows the Van de Graaff with the terminal and the analyzing magnet.

Terminal and ion source

The axial extraction PIG ion source (IQ in fig. 2) has now been used for about 5 months in the Van de Graaff with an average lifetime of 180 h [8]. It provides sufficient beams of doubly charged ions (table 3). It is our first choice due to its small size, reliability, little power consumption and cooling requirements which all are essential in the Van de Graaff terminal. Later on more complex sources for higher charge states might be adapted to the Van de Graaff terminal. Now the efforts are concentrated on finishing the final principle is shown in fig. 2. The extracted beam is focused by Einzel lens 1 (EL1) through a Wienfilter (WF) for charge state selection. Einzel lens 2 (EL2) and a variable voltage acceleration gap produce the correct shape and velocity of the beam at the narrow prebuncher tube. The next variable acceleration (GAPL) adjusts the correct entrance energy into the acceleration tube and the third Einzel lens (EL3) the focusing.

All the mechanical elements of the vacuum envelope and inside it have been fabricated, the pumping scheme with a turbomolecular pump and one ion getter pump tested in the Van de Graaff. At present the power supplies and control electronics including the interfacing for adjustment and readout through an infrared data transmission and tested. Great care is taken to filter and shield the electronics against high voltage transients from sparks.

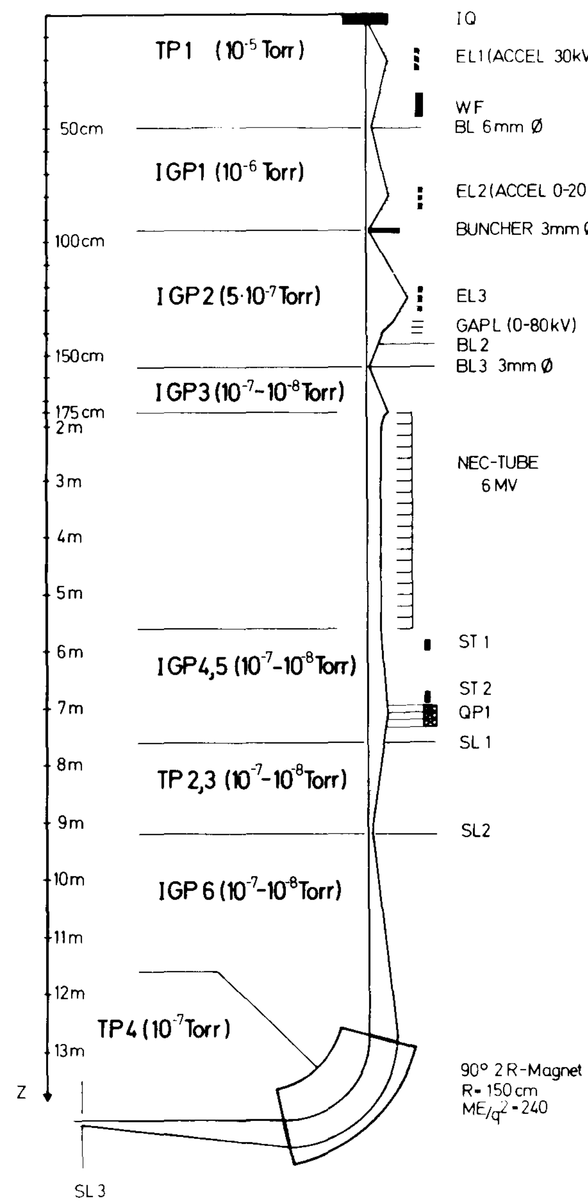

Fig. 2 Van de Graaff: Pumping scheme, beam envelope and optical elements

Gas	I µA				$E_{80\%}$ · m mrad			
	Molecule	1^+	2^+	3^+	Molecule	1^+	2^+	3^+
$^1H_2$	370	40	-	-	30	65	-	-
^3He	-	225	1.2	-	-	70	85	-
N_2	870	120	6	-	100	65	80	-
Ne	-	480	50	-	-	110	60	-
Ar	-	600	54	5	-	60	35	40

Table 3: Currents I and Emittance E of the axial extraction Penning source. The emittance has been measured at 23 q·keV. The energyspread is E 80 q·eV.

Beam matching

The beam matching between Van de Graaff and cyclotron (see fig. 1) as described in detail in ref. 9, 10 comprises as main element the stripper. In a series of measurements for various ions and energies the charge state distribution, equilibrium thickness, angle scattering[11] and energy straggling[12] have been measured. The results on angular scattering are summarized in fig. 3 in terms of the reduced quantities as defined by Meyer[13]. Clearly the theory is correct and can be used to predict the angle straggling. The energy loss straggling is higher by a factor of 1.5 to 2.0 than calculated from collision straggling. Charge exchange straggling had to be taken into account to explain the experimental findings. Fig. 4 shows a measurement of charge state distribution and energy straggling. We now can predict precisely enough how the stripper influences the beam for our range of ions. The only open question is lifetime and degradation of stripper foils. The final stripper is being fabricated now. It is a gas target differentially pumped by means of two cryopumps, which can quickly be exchanged for foils.

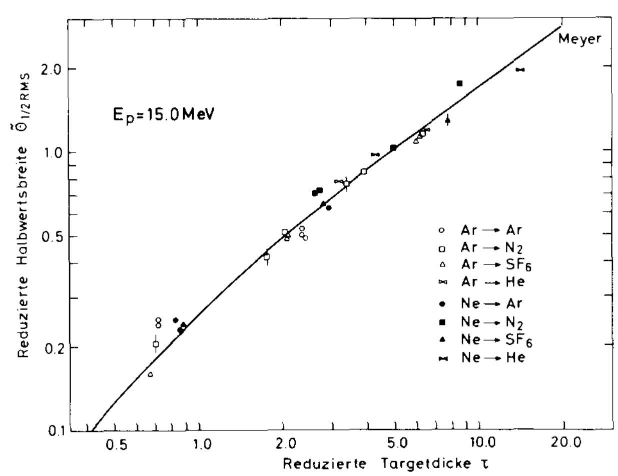

Fig. 3 Angle straggling in gases (see text)

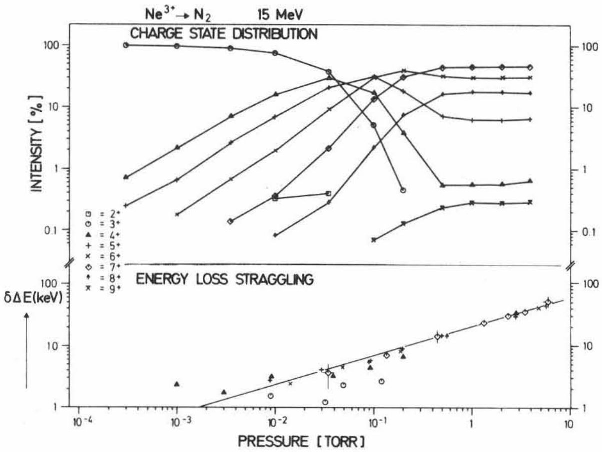

Fig. 4 Charge state distribution and energy straggling versus target thickness (1 torr = 6.7 $\mu g/cm^2$)

To minimize the increase in phase space due to angle and energy straggling in the stripper a sharp focus at the stripper in time and horizontal and vertical directions is required (fig. 5). The first Klystron buncher and the magnetic elements between Van de Graaff and stripper accomplish this. The area of each of the three phase planes is increased by less than a factor 2 by the stripper. The emittance in both planes changes from 6π mm mrad to less than the acceptance of the cyclotron of 10πmm mrad. The following elements after the stripper guide the beam achromatically to the second buncher which refocuses it to less than 6° phase width in the center of the cyclotron. Lenses q6 and q7 adjust the horizontal and vertical phase space as required for injection. With quadrupole q8 the total energy dispersion can be varied as wanted and finally q9 gives the wanted combination of spatial and angular dispersion.

The prebuncher in the terminal of the Van de Graaff gives 50 % of the intensity of the source in 60° of phase behind the Van de Graaff which in turn are compressed into 6° at the cyclotron center without intensity losses. Taken together with the roughly 30 % abundance of the charge state selected after the stripper 15 % of the beam from the source will theoretically be accepted by the cyclotron and should be accelerated and extracted with very little losses with roughly 10^{-3} energy resolution.

Cyclotron

The responsibility for the cyclotron from design to running in is with Scanditronix. In the following is reported about their work.

The main technical parameters are given in table 2, a sketch of what the machine will look like in fig. 6 and a layout in fig. 7. In the sketch one sees the injection beam line in the lower left corner and right of it a differential probe. One RF-resonator sticks out to the right, the belonging power amplifier is the box on the platform on top of the magnets. The cryopumps sit on the dee-free valleys connected to the chamber by valves of 500 mm diam. opening. Below the vacuum tank one turbo-molecular pump is visible.

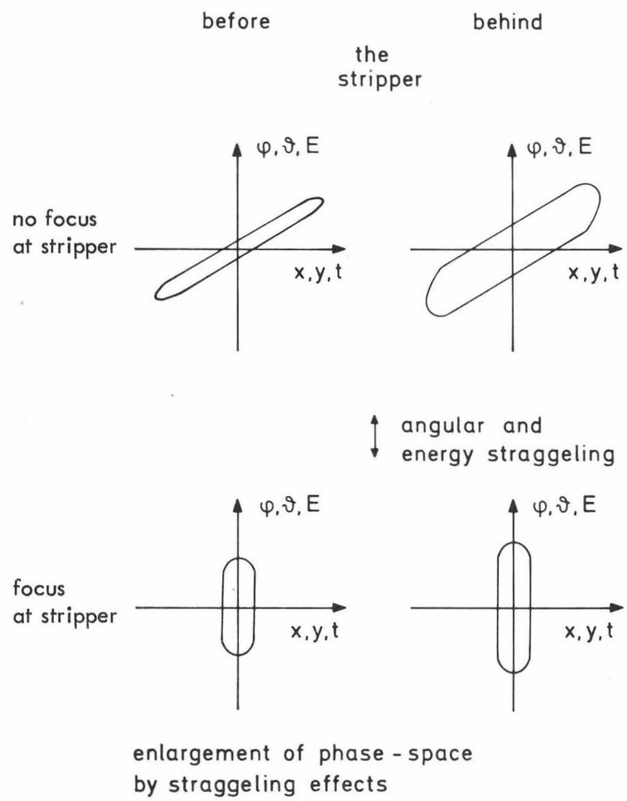

Fig. 5 Enlargement of phase space due to straggling in the stripper for two different conditions

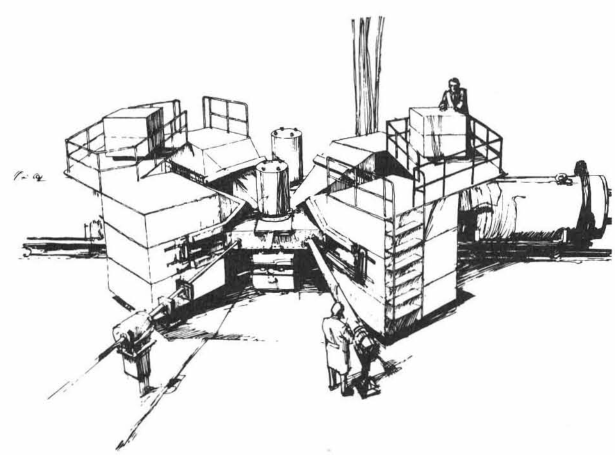

Fig. 6 Artists view of the cyclotron

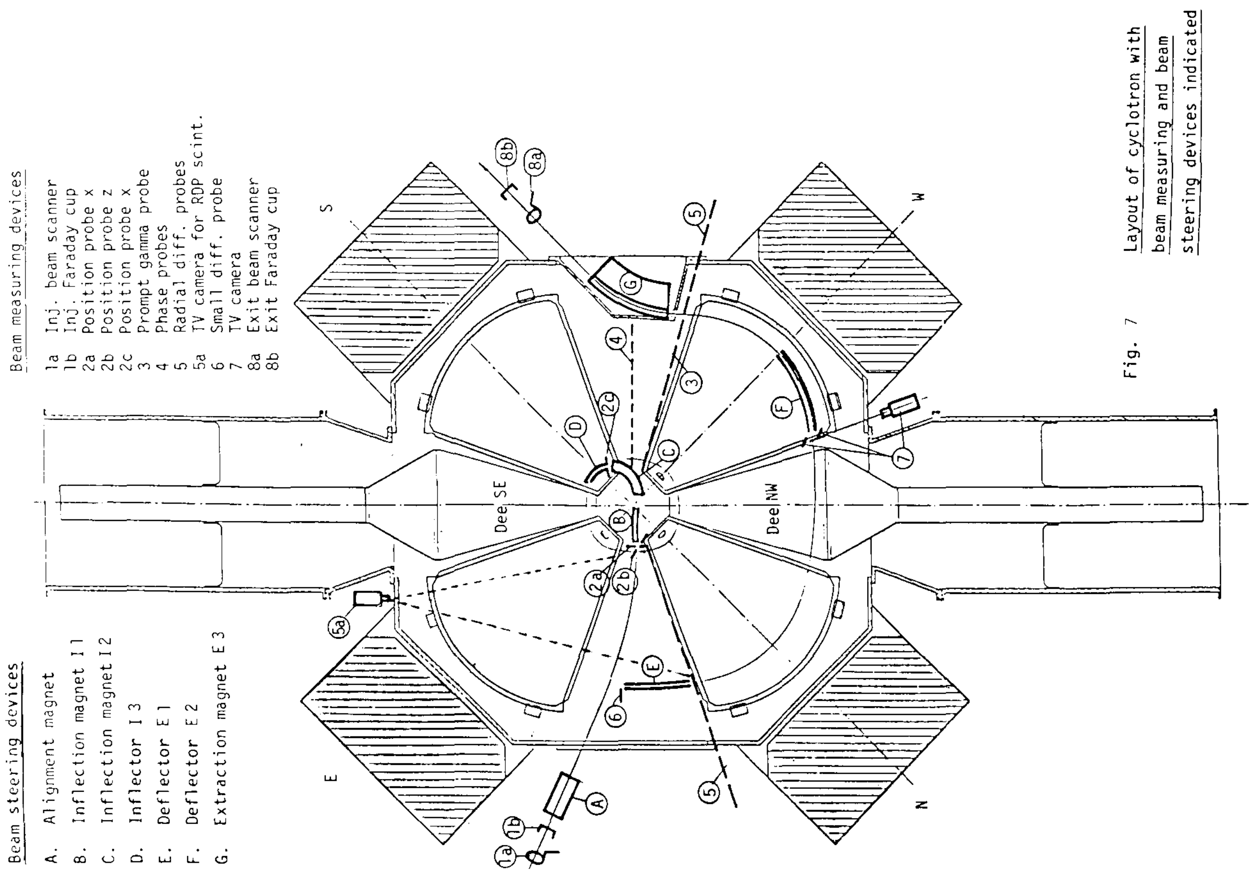

Fig. 7 Layout of cyclotron with beam measuring and beam steering devices indicated

Magnets

The magnetic system was extensively studied by calculations and measurements on a half scale model consisting of two full sector magnets and two magnets that resembled the center tips and were activated by coils around the yokes. From the measurements the final shape of the radial pole edges was determined to be close to an isochronous field for 50 MeV deuterons which present an intermediate relativistic correction. The dependence of the field in the valleys and the hills on excitation is nearly identical as it was aimed for. This means that the injection path through the valley is the same for all particles, minor deviations can be compensated by the injection elements in the central region. Also the magnetic disturbances due to the injection and extraction elements have been studied and compensatory shimming installed and tested. The measured fields due to pole face windings could be reproduced by calculations. The model measurements are finished now. Three of the final magnets have been assembled at Scanditronix and aligned relatively to each other within ± 0.15 mm tolerances. The fourth magnet which includes a full set of pole face windings should also be assembled and aligned by the time of the conference. The first magnet has been fully excited to 16.3 kG. The tip of the yoke then moved down 1 mm which poses no problem. The 300 kW main power supply is ready except that the stability still has to be improved to achieve the ambitious goal of $2 \cdot 10^{-6}$. The trimcoil supplies are under construction. Each magnet will permanently be equipped with a fixed NMR probe that might perhaps be used for field regulation. This is part of a general multiplexed NMR-system with 25 probes for supervising also all beam line magnets under computer control.

The field measuring equipment is ready for use. The main measuring machine consists of 74 flip coils mounted in a bar that rotates around the center. The accuracy is ± 1 G at 16 kG, the mesh can be 0.2° times 1 cm in radius. A 360° field map for r> 46.0 mm can be taken in one working day, including the necessary preparations. The system is interfaced to a PDP 11 computer and works automatically with output on magnetic tape. A very similiar system with 40 coils has been used on the model. Three additional smaller flip coils systems and a Hall probe will be used for the central region and inside the extraction elements which are not accessible to the main device. The aim is to get sufficient field data so that the settings for any wanted beam can be interpolated.

The complete magnetic system including injection- and extraction elements will be assembled and the field maps taken at the site of Scanditronix. In spring 76 the magnets will then be delivered to Berlin.

Magnet system

4 separated C-magnets	
Nominal width	50°
Pole gap	uniform 6 cm
Pole radii	0.306-2.054 m
Beam radii (mid magnet)	0.45 -1.89
E_{extr}/E_{inj} (non relativistic)	16.8
Pole edges	Rogowski shape
Homogenizing gap between yoke and pole	
Sector field	0.5 -1.55 T
Corresponding mass energy product	A E/q^2=12-120 MeV
Field stability	$5 \cdot 10^{-6}$
Field flutter	0.63-0.82
Radial betatron frequency	1.06-1.14
Vertical betatron frequency	0.65-0.82
Weight of one sector	100 t
4x2 main coils of 2000 A x 30 turns	
Total power consumption	300 kW
4x2 harmonic coils included in main	
Coils of 40 A x 37 turns	
4x2x12 pole face windings of 200 A x 2 turns	
The one or two innermost and the outermost butone can be driven harmonically	
Total trim coil power	24 kW

RF-system

Two independently driven identical systems	
Dee angle	36°
Gap voltage	100 kV
Minimum gap width	32 mm
Voltage stability	10^{-3}
Frequency range	8-20 MHz
Frequency stability	10^{-6}
Harmonic number	2,3,4,5,6,(7)
Inter-Dee phase stability	1°
Straight coaxial resonators	
Length of resonator from cyclotron center	5 m
Resonator diameter	1.5 m
Rough tuning	moving short
(Below 10 MHz the capacity is increased by flaps)	
Fine tuning	capacitive
Q-value	$>$ 5000
Drive	50 kW amplifier
Coupling	inductive

Vacuum system

Design pressure	$1\text{-}5 \cdot 10^{-7}$ torr
2 cryopumps (3 K) each	10 000 l/s
2 turbo molecular pumps each	450 l/s
2 rough pumps each	35 m^3/h
All metal sealed system	
Pole pieces and pole face windings inside vacuum	
Vacuum tank diameter	4.6 m
Vacuum tank height	0.64 m
Total vacuum surface (macroscopic)	300 m^2
Total vacuum volume	20 m^3

Table 2: Main technical parameters of the VICKSI-cyclotron SPC 120

RF-system

The RF-system follows the classical cyclotron design, especially Harwell and Stockholm. Straight cylindrical resonators extend radially outward from the 36° Deltas in two valleys, course tuning is by moveable shorts. After some considerations of less floor space requiring systems we adapted this approach to avoid surprises with any new system that might cause big delays. The frequency range of 8-20 MHz, the voltage of 100 kV, and the requirements for 10^{-7} torr vacuum taken together are anyway encountered for the first time and require much technological skill in all details. Flat topping was excluded from the beginning since the research program emphasizes the use of short beam pulses.

The cavities and dees are developed at Nucletec/Geneva a sister company of Scanditronix who does all the electronics including the power amplifiers. After full power tests in Geneva the RF will be delivered to Berlin in mid 76. One cavity with the Dee stem, cantilever mechanism, the mechanism for moving the short and with provisional dee, dummy dee, flaps and short have been mounted. The purpose of the flaps is to increase the Dee capacity to reach the frequency range of 8-10 MHz. Measurements on this configuration have lately fixed the design of the coupling loop and anode circuit of the final amplifier which are now being detailed. One final dee has been delivered, the shorting pistons are in production after successfull tests of one sector. According to the latest measurements the Q of the resonators will exceed 5000 which gives a safe margin on the amplifiers that had been designed for Q=3000. One amplifier is being assembled now and all the power supplies are near completion.

Vacuum

The main vacuum chamber will be octagonal with large rectangular flanges in the valleys at the outer rim for access to injection and extraction elements, probes, and to attach the RF. Big flanges are also provided at top and bottom of the central region. The bottom and top covers go through the homogenizing gaps between yokes and poles, the latter ones with the pole face windings are in the vacuum. The top plate has four large openings. The upper and lower pole piece with the pole face windings and a vacuum cover plate containing all feed throughs will be assembled externally, then lowered into the chamber, and the cover plate lip-welded to the tank. All other seals are made with metal gaskets. The stainless steel chamber has been ordered from a subcontractor who shall deliver it to Berlin in spring 76.

The main pumps are two cryopumps as designed for the CERN ISR by C. Benvenuti[14]. They use liquid Helium of about 3 K which insures a pumping speed of at least 10 000 l/s for anything (except Helium). Hydrogen, which becomes of main concern at 10^{-7} torr, is pumped even more effectively than air. The pumps are ready for final assembly. The 500 mm opening valves for separating the pumps from the tank are delivered. Two 450 l/s turbomolecular pumps will be used for pumping down and to take care of Helium. Depending on the performance of the system additional pumping behind the RF-pistons and a high capacity roughing pump might have to be added.

The main problem encountered is to find mechanical constructions for all the anyway complicated parts of RF, deflectors, probes etc. that conform with 10^{-7} torr vacuum standards and allow for reasonable leak checking. Baking of the system is in general impossible however for the first pumpdown some parts might be heated moderately.

Beam diagnostics

The diagnostics tools are shown in fig. 7. The two radial differential probes are foreseen to be equipped with 4 exchangeable heads each of which combines 2 or 3 of the following measuring schemes: total current, differential current, vertically moveable pin, five fingers, scintillator phase pick up. Ten fixed phase probes and a moveable γ-detector out of the vacuum that uses a differential probe as target will measure phases. Special probes are provided to check the injection and extraction path.

Injection and extraction

There is a separate contribution to this conference on injection[15]. Based on the field maps from the model, extraction has been worked out quantitatively also on the computer. The next to last trim coil can excite the ν_r=1 resonance by a first harmonic of 2-3 Gauss. The last coil and a slight decrease of the sector width give a negative radial field gradient and let ν_r drop below 1. 10 mm turn separation are easily obtained and close to 100 % extraction efficiency is expected. Non linear distortions are negligible.

The injection and extraction elements are partly in fabrication and partly mechanical details of adjustment etc. are designed. The electrostatic deflectors (I3 and E1, fig. 7) have been tested, the magnetic elements measured largely in the model.

Orbit dynamics

The main work at Scanditronix has been to analyze the measured field maps numerically and in an iterative procedure pin down the details of all the optically active elements. All problems from injection to extraction including the matching to the beam handling systems seem to be solved to full satisfaction now, pending verification by a real beam. Besides, in cooperation with H. L. Hagedoorn and W. Schulte / Eindhoven a semiquantitative analytical approach to the orbit dynamics is being persued in order to get a better understanding and feeling of the orbit dynamics which will be very valuable in running in the machine. A contribution to this conference deals with the radial-longitudinal coupling[16].

Beam handling

The beam handling (fig. 1) has been described in detail[17,18]. Most of the 10 target positions are reached through double monochromator systems which allow for nearly any wanted mode of beam preparation, namely e.g. doubly dispersive, fully achromatic, fully isochronous combined with the possibility to define energy spred and likely pulse width between the two dipole magnets. A special feature is the vertical beam at location TV1 for liquid targets. The detailed mechanical design is finished and components are being ordered. Installation is scheduled to start in January 77 after the cyclotron has been assembled.

Computer Control

The whole accelerator and beam handling system will be computer controlled, however closed loop regulation through the computer is not foreseen for the near future. A schematic sketch is shown in fig. 8. The actual devices are controlled by 5 standard types of Camac modules with an additional bus for analog measurements. One module completely controls one device which gives a very clear scheme. Nearly all of these modules have been delivered. The control desk follows the LAMPF, Super CERN design. Components are being ordered. Installation will start in January 76. The software is being developed, a preliminary version is being checked on a test section of beam line with the Van de Graaff beam. A separate contribution to this conference gives details of the control system[19,20].

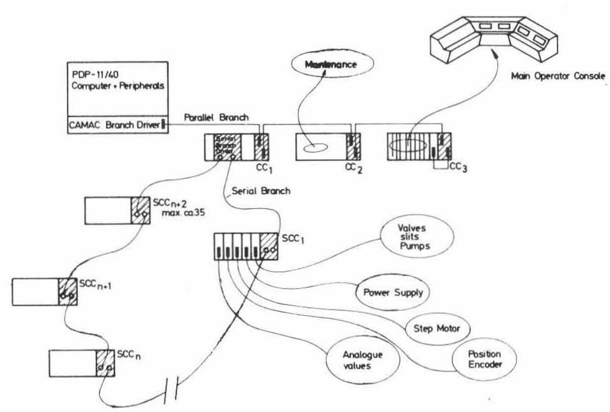

Fig. 8 Principle of computer control

Building and installations

Newly to be erected were the cyclotron vault with rooms for the power supplies, electronics, main power distribution and cooling water and air conditioning facilities plus some space for experiment electronics. Construction started in spring 74 and the roof was up in February 75. The main transformer station (5x800 kVA) has been accepted and now the power lines to the consumers are being installed. The main cooling water system is a closed, deionized water circuit with a cooling capacity of 1.7 MW. The inlet temperature will be about 26° C and the average temperature rise 10° C. The cooling towers and heat exchangers are finished and now the stainless steel pipes are being installed. There is also a 6° C water circuit mainly for air conditioning. In the experimental hall now concrete shielding and a foundation for a magnetic spectrometer are put in. The old control room is being redone.

Radiation safety

Radiation levels during operation can vary by five orders of magnitude depending on the beam required by an experiment. The concept of the safety system must be accordingly flexible to maintain safety without unreasonably restricting the working possibilities. This is accomplished by permantly monitoring the radiation at all areas of interest and based on these measurements automatically allow access or not, give warnings and in case of danger interrupt the beam. A major effort will be made to keep the source strengths themselves down in the cyclotron, the beam handling system, and in the beam dumps. With this accelerator combination there are efficient possibilities to discard of beam, that would be lost later anyway, already before the cyclotron without producing radiation. This and if possible using Carbon where the beam might hit should also keep activation low.

Conclusion and outlook

This report tried to cover the work of now about 120 people half of them at Scanditronix and half at HMI. No really bad problems have occured so far, the many smaller ones could be overcome expecially through good and close cooperation between everybody. The future schedule is to have the building ready at the end of this year. In 76 the cyclotron will be installed in Berlin which means that magnets, RF, and vacuum come together for the first time. In parallel the beam for injection will be developped. In 77 then the cyclotron will be run in with beam and the beam handling for the experiments installed. Judging from the previous progress, though now a delay of half a year compared to the original schedule exists, we have a good chance to start experiments around end of 77.

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DISCUSSION

Y. JONGEN: It seems from the early design that the maximum energy of the cyclotron has been increased from K = 90 MeV q^2/A to K = 120 MeV q^2/A. Does this correspond to an increase in maximum field or extraction radius?

K.H. MAIER: We always had two figures, we had a guarantee from Scanditronix that it would reach 100, whilst, in fact, it was designed to reach 120. In the meantime we feel safe to say it will reach 120, before we were more careful and stated 100. I do not think it ever was 90.

H.G. BLOSSER: What is the field strength in the central inflection magnet?

K.H. MAIER: It is practically the same as in the main magnet and the main magnet runs at a full excitation at 15.4 kG.

S. ADAM: Why do you not use a tandem as injector?

K.H. MAIER: We have a Van-de-Graaff (our old one which is undergoing reconstruction). We have plans for a second injector to reach higher energies, most likely a cyclotron or a tandem. However, these plans have been postponed.