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Institut für Kernverfahrenstechnik

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Status Report as of December 1973

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DEVELOPMENT AND CONSTRUCTION OF AN INJECTOR USING HYDROGEN CLUSTER IONS FOR NUCLEAR FUSION DEVICES

Status Report as of December 1973

by

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Abstract

The heating of thermonuclear plasmas by the injection of accelerated particles has become a favoured method during the last few years. One of the problems involved is to achieve beams of comparatively high flux densities. As space charge is the physical barrier which limits the flux density of charged particle beams, cluster ions with low charge-to-mass ratio are expected to be an appropriate means to diminish this difficulty. A second property of the clusters is their broad mass distribution due to their statistical growth process. Since all clusters have the same energy after being singly ionized and accelerated the mass distribution is transformed into a velocity distribution. This in turn should be useful to counteract the growth of plasma instabilities.

To study the interaction of clusters with a plasma the Max-Planck-Institut für Plasmaphysik, Garching (IPP) and the Institut für Kernverfahrenstechnik, GfK Karlsruhe (IKVT) agreed that a cluster injector should be developed by the IKVT and finally transferred to the IPP for injection experiments on the Wendelstein VII-Stellarator. To provide a relevant amount of beam power for heating the W VII-plasma the design data of the cluster-injector are: 10 A equivalent beam current of neutral hydrogen atoms, 1 MV accelerating voltage, 10^2 hydrogen atoms per cluster mean size of the singly ionized clusters corresponding to a beam power of 100 kW. The high voltage generator is almost completed and available for preliminary experiments on the high gradient acceleration of cluster ions at the Institute of Nuclear Physics of the University of Lyon. The injector structure and the cryostat for the cluster beam source will be manufactured by industry during the next two years. In the meantime the ionizer of the 10 A equivalent cluster beam will be developed by IKVT and experiments dealing with the neutralization of 1 MeV cluster ion beams will be carried through with the low current 1 MV accelerator of the Institut für Aerobiologie (IFA) of the Fraunhofer Gesellschaft in Grafschaft, Germany.

Zusammenfassung

Die Injektion beschleunigter Teilchen wird seit einigen Jahren als vorteilhaftes Verfahren zur Heizung thermonuklearer Plasmen angesehen. Eines der dabei auftretenden Probleme ist die Erzeugung verhältnismäßig hoher Stromdichten. Die Stromdichte elektrisch geladener Teilchenstrahlen ist durch ihre Raumladung begrenzt. Die Verwendung von Clusterionen mit niedriger spezifischer Ladung läßt daher eine Erleichterung dieses Problems erwarten. Eine weitere charakteristische Eigenschaft von Clusterstrahlen ist ihre breite, durch den statistischen Prozess des Clusterwachstums bewirkte Massenverteilung. Durch die Beschleunigung auf dieselbe Energie wird bei einfach ionisierten Clustern die Massenverteilung in eine Geschwindigkeitsverteilung transformiert. Diese sollte geeignet sein, dem Wachstum von Plasmainstabilitäten entgegenzuwirken.

Zur Untersuchung der Wechselwirkung von Clustern mit Plasmen wurde zwischen dem Max-Planck-Institut für Plasmaphysik (IPP), Garching und dem Institut für Kernverfahrenstechnik (IKVT) der GfK, Karlsruhe, vereinbart, daß IKVT einen Clusterionenbeschleuniger für Injektionsexperimente am Wendelstein VII-Stellarator des IPP entwickelt. Im Hinblick auf die für die Heizung des W VII-Plasmas notwendige Strahlleistung von 100 kW sind folgende Auslegungsdaten für den Clusterinjektor vorgesehen: ein Wasserstoffatomstrom von 10 A, eine Beschleunigungsspannung von 1 MV, und eine mittlere spezifische Größe der Clusterionen von 100 Atomen pro Ladung. Der Hochspannungsgenerator steht vor seiner Fertigstellung und ist anschließend für erste Experimente zur Hochgradient-Beschleunigung von Clusterionen am Institut für Kernphysik der Universität Lyon verfügbar. Mit der Fertigstellung der Injektorstruktur und des Kryostaten für die Clusterstrahlquelle wird innerhalb der nächsten zwei Jahre gerechnet. In der Zwischenzeit werden von IKVT der Ionisator für den Clusterstrahl mit einem Teilchenstrom von 10 A entwickelt und an einem für kleine Ströme ausgelegten 1 MV-Beschleuniger des Instituts für Aerobiologie (IFA) der Fraunhofer Gesellschaft in Grafschaft Experimente zur Neutralisierung von 1 MeV-Clusterionenstrahlen durchgeführt.

Contents

1. Introduction

The Institut für Kernverfahrenstechnik (IKVT) submitted in July 1972 a report[1] referring to the planning basis of the Fusion Injector Project. This report contained a proposal for construction of an accelerator for hydrogen cluster ions. According to an agreement with the Max-Planck-Institut für Plasmaphysik (IPP) at Garching this injector is to be used at the Wendelstein VII stellarator under construction at the IPP. With respect to the operating data provided for the Wendelstein VII the injector has been designed to have an accelerating voltage of 1 MV, a particle current of 10 A and a particle energy of 10 keV per atom.

The experiments to be conducted with Wendelstein VII primarily will support research into problems of plasma heating by injection of clusters. In addition, the applicability of the recently developed "low radius start up" concept[2] of a fusion reactor can be tested. Moreover, studies on the interaction between large clusters and the plasma can contribute to a solution of the problem of continuously feeding fuel to a reactor in steady state operation.

In the basic planning report[1] three alternatives of the technical design of the cluster ion accelerator were discussed. Also in the interest of shortening the development time for the injector as much as possible, further work was concentrated on the version with a cluster ion beam source at high voltage potential. In this version a drift section in the electric field for the clusters is avoided and therefor the physical risk minimized. The technical feasibility of this concept was ensured in cooperation with industry+) by drafting the documents for the construction of an injector within the framework of an engineering study. The future setup of the injector at Garching was cleared in accordance with IPP[3]. According to estimates of the industry, the construction of the injector will take approximately two years++).

Below, first, the status of physical development work concerning the various injector components is reported on. Then the concepts of the high voltage injector structure, which was arrived at in cooperation with industry, the time schedule and the financial and personnel framework of the project will be described.

+) High Voltage Engineering Europe, Netherlands

++) The high voltage generator has already been ordered with the Emil Haefely Company, Switzerland, because it will be required for the early experiments on high gradient acceleration of cluster ions (see Section 2.2).

2. Physical Development Work

2.1 Development and Construction of a Cluster Ion Beam Source for a Particle Current of 10 A.

For the injector a steady state accelerated beam with a hydrogen atom current of 10 A with an energy of the accelerated H-atoms of 10 keV is being aimed at. The specific size of the cluster ions is fixed at 100 atoms per charge by designing the high voltage generator to work at a voltage of 1 MV. Cluster ions of this specific size can be generated by electron impact ionization of neutral clusters consisting of 10^4-10^5 H-atoms. Fig. 1 for instance shows a cluster ion spectrum of an average specific size of 300 H-atoms per charge[4).

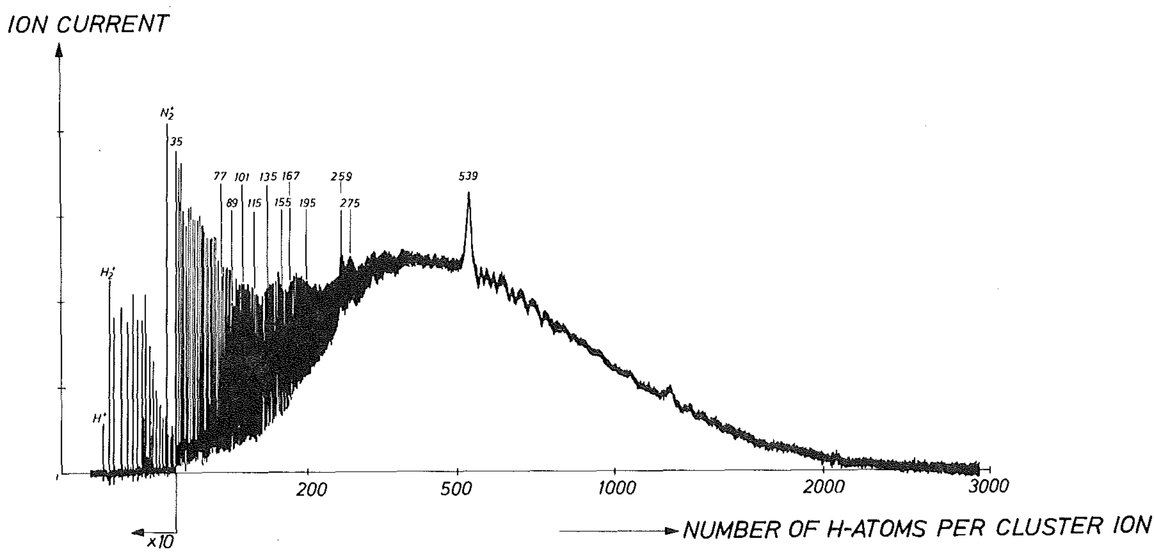

Fig. 1: Cluster ion spectrum generated by electron impact ionization of clusters of approximately 10^4 H-atoms. The cluster ions contain on the average 300 H-atoms per charge.

The design of the electron impact ionizer[5] used to produce the cluster ions with the mass spectrum represented in Fig. 1 is shown in Fig. 2. The electrons are emitted

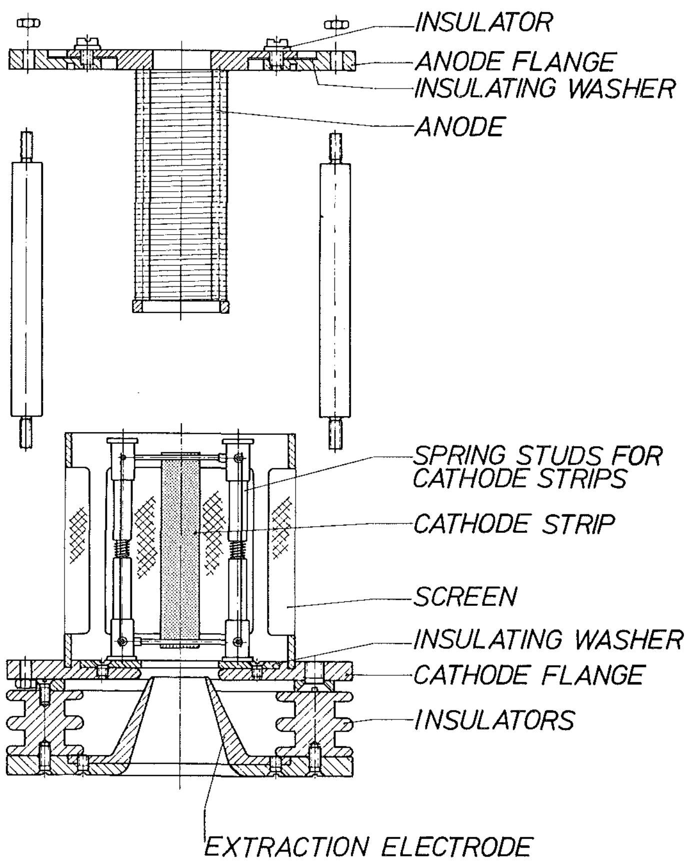

Fig. 2: The electron impact ionizer shown on this diagram was used to produce the cluster ions with the mass spectrum shown in Fig. 1.

by four oxide cathode strips arranged along the sides of a square. The electrons are accelerated into the cluster beam by the anode grid. The cluster ions generated by impact ionization are extracted from the ionizer by an insulated extraction electrode.

The production of cluster beams with the necessary atom current of 10 A is aggravated, on the one hand, by the required relatively small size of the clusters[6], on the other hand, by the relatively high current density of atoms needed in view of the dimensions and the arrangement of the ionizer. Extensive test series and the similarity laws[7][8] elaborated for condensation in nozzle flows were used to develop cluster beams with the properties likely to be required for ionization purposes[9]. Fig. 3 is a diagram of a typical intensity profile of these cluster beams. In the required range of cluster sizes current densities of atoms in excess of 30 A/cm^2 and an atom current usable by collimation of up to 30 A was achieved.

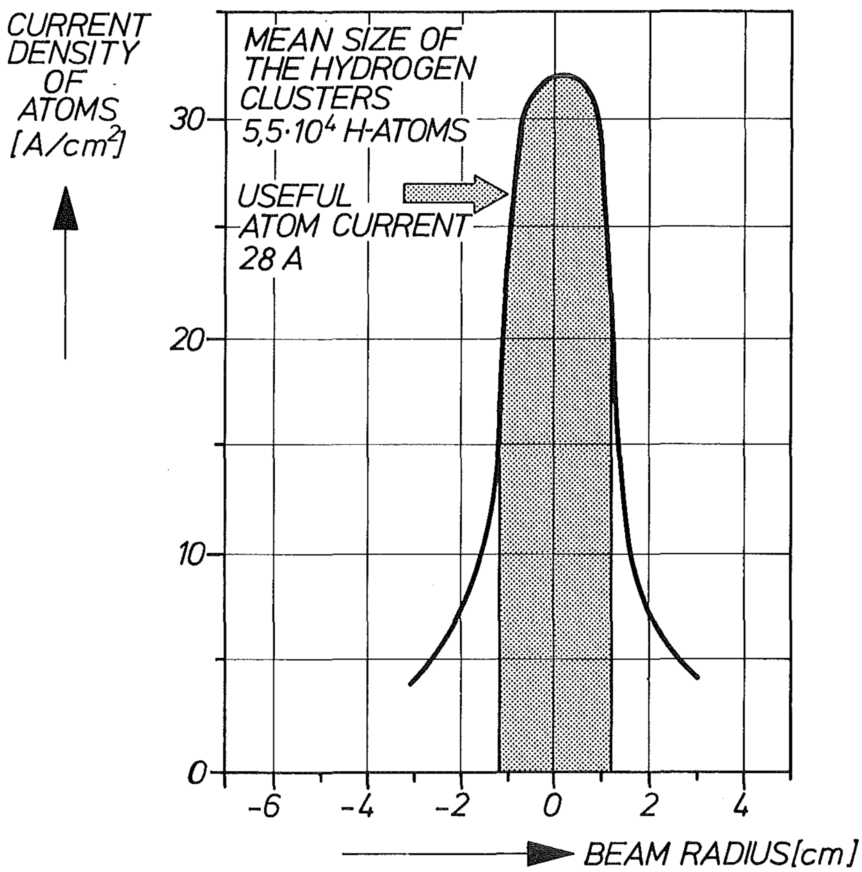

Fig. 3: Intensity profile of a hydrogen cluster beam with an average cluster size of approximately 5.5 x 10^4 H-atoms probably required for ionization.

Because of the limited pumping capacity of the existing molecular beam equipment the duration of these intensive cluster beams had to be limited to the order of a few milliseconds. These beam times are too short for steady state operating conditions to be established in the ionizer. Accordingly, the ionization studies were performed on steady state, but low intensity cluster beams in which the attainable ion currents were limited to approximately 1 mA. With regard to later quasi-steady state operation of the injector with an ion current of 100 mA studies will be conducted on the ionization of steady state cluster beams with atom currents of 10 A in order to optimize the cluster ion beam source. For this reason, a test facility[10)] equipped with cryo-pumps of the necessary capacity was commissioned for the generation of high current steady state cluster beams. The test facility is designed for the use of ion extraction voltages up to 150 kV, thus permitting the simulation of extraction conditions[11)] most probably required for the injector. Work on the test facility will be concentrated upon the optimization of the emittance of the cluster ion beam source.

2.2 High Gradient Acceleration of Cluster Ions to 1 MeV

In order to achieve high current densities the cluster ions must be accelerated to their final energy over a short distance, i.e. in a high potential gradient. An experiment regarding high gradient acceleration of cluster ions to an energy of approximately 1 MeV is being prepared in cooperation with the Institut de Physique Nucléaire of the University of Lyon (IPNL). Fig. 4 shows the planned test assembly with the cluster ion beam source, the high gradient accelerator tube and the beam diagnostic. The 120 mA/1 MV high voltage generator with pressurized gas insulation which is to be used in the

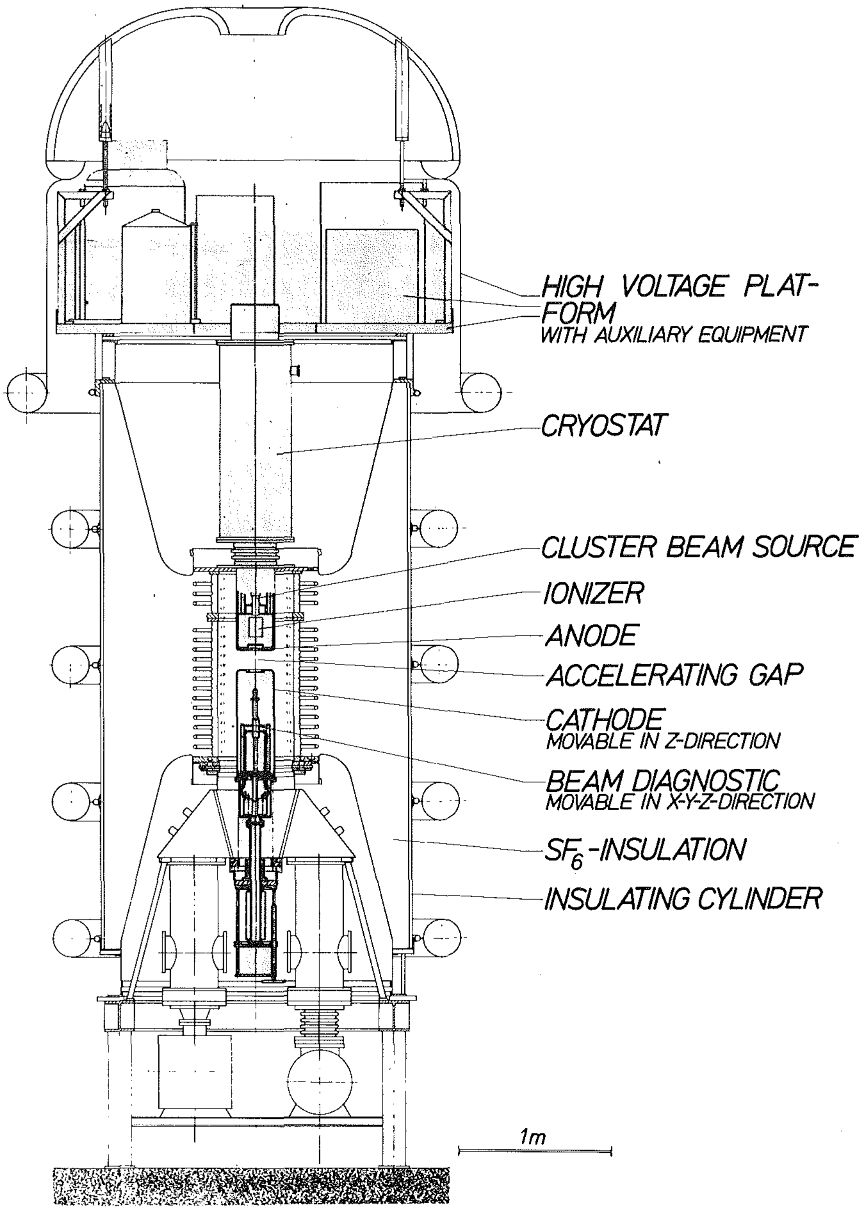

Fig. 4: Schematic diagram of the test assembly on high gradient acceleration of cluster ions to an energy of 1 MeV at Lyon. The shaded areas indicate the amount of alterations of the existing accelerator necessary for the experiment. The high voltage generator and the motor generator supplying the cluster ion beam source are not shown on the diagram.

experiment and subsequently in the injector will be supplied by mid-1974. This work is intended, above all, to provide operating experience in high gradient acceleration of cluster ion beams of high current density. Operation of the injector will profit especially from experience concerning the generation of secondary particles by high energy cluster ions, the intensity of the X-rays encountered, the dielectric strength of the neutral cluster beam, and problems of ion optics and beam diagnostics.

The preparations for this experiment presently under way at IPNL and IKVT include the construction and testing of a cluster ion beam source with the auxiliary systems necessary for operation[12], a pair of accelerating electrodes for installation into the accelerator tube made available by CERN, a telemetry system[13] for control of the function of the cluster ion beam source at high voltage, a system for measuring the beam parameters[14] with the associated systems for data acquisition and processing and, finally, the modification of the high voltage electrodes in which the cluster ion beam source and the auxiliary systems will be mounted.

Modifications of the structure of the high voltage systems and the test of the first accelerating electrodes fabricated by CERN were performed at IPNL. A test facility was set up at IKVT in which the function and interaction of all components are tested under the most realistic conditions possible. The cluster beam source and the telemetry system were successfully tested. After the end of the current ionizer test the experimental set-up will be established at Lyon in late spring 1974.

2.3 Development and Construction of a Neutralizer for MeV Cluster Ions

The neutralization of cluster ions should be possible with at least the same efficiency as that of atomic ions, given the same energy per atom, because it must be expected that an equilibrium will be established in a sufficiently thick gas target between charge exchange and impact ionization. This is confirmed by earlier experiments in which cluster ions accelerated with a voltage of up to 150 kV were neutralized even at a relatively thin water vapor target with efficiencies in excess of 90 %[15][16]. As higher accelerating voltages are used, the cross sections relevant to the process will change. At low energy per atom elastic collision processes of the target particles in the cluster dominate, which may result in a heating and subsequent evaporation of the clusters. At higher energies, however, inelastic collisions between target particles and atoms in the cluster play a major role. Accordingly, in the experiments conducted at the accelerator of the Institut für Aerobiologie (IFA) of the Fraunhofer Gesellschaft at Grafschaft the neutralization of cluster ions will be studied with the size and energy of clusters planned for the injector. The maximum possible accelerating voltage is around 1.2 MV. The experiments are to clarify the efficiency of neutralization, the necessary thickness (torr cm) of the gas target and the amount of broadening of the accelerated beam due to scattering at the gas target.

Any influences of a high particle current upon the gas target and its reaction on the process of neutralization of course cannot be studied at Grafschaft. However, in this respect experience with gas targets is available for the charge exchange of proton beams with a few amperes. In this case[17] obviously no major problems were encountered. In the neutralization of cluster ions it must also be anticipated that the current to be removed from the gas target is much lower than for atomic ion beams because the electric beam current is lower by a factor of 100 for the same particle current.

Attachment of the cluster ion beam source[18] to the accelerator tube was finished in September 1972. Fig. 5 shows the cylindrical cryostat of the cluster ion beam source attached to the accelerator tube underneath the high voltage dome of the accelerator, which has been removed. Experiments so far[19] have been conducted mainly to fit the cluster ion beam source to the relatively unknown beam optics of the accelerator tube and to test suitable methods of measurement in order to determine the accelerated ion and mass currents. As a result of preliminary experiments a modified Faraday cup was developed which allows the ion current to be measured within a factor of 2 despite secondary particle currents higher by several orders of magnitude. In 1974 the experiments will be continued with a scattering chamber adapted to conditions at Grafschaft. Along with the neutralization experiments further improvements are planned to increase the reliability of current measurements. The results of these experiments will be used in 1975 in the design and construction of the neutralizer to be used with the injector.

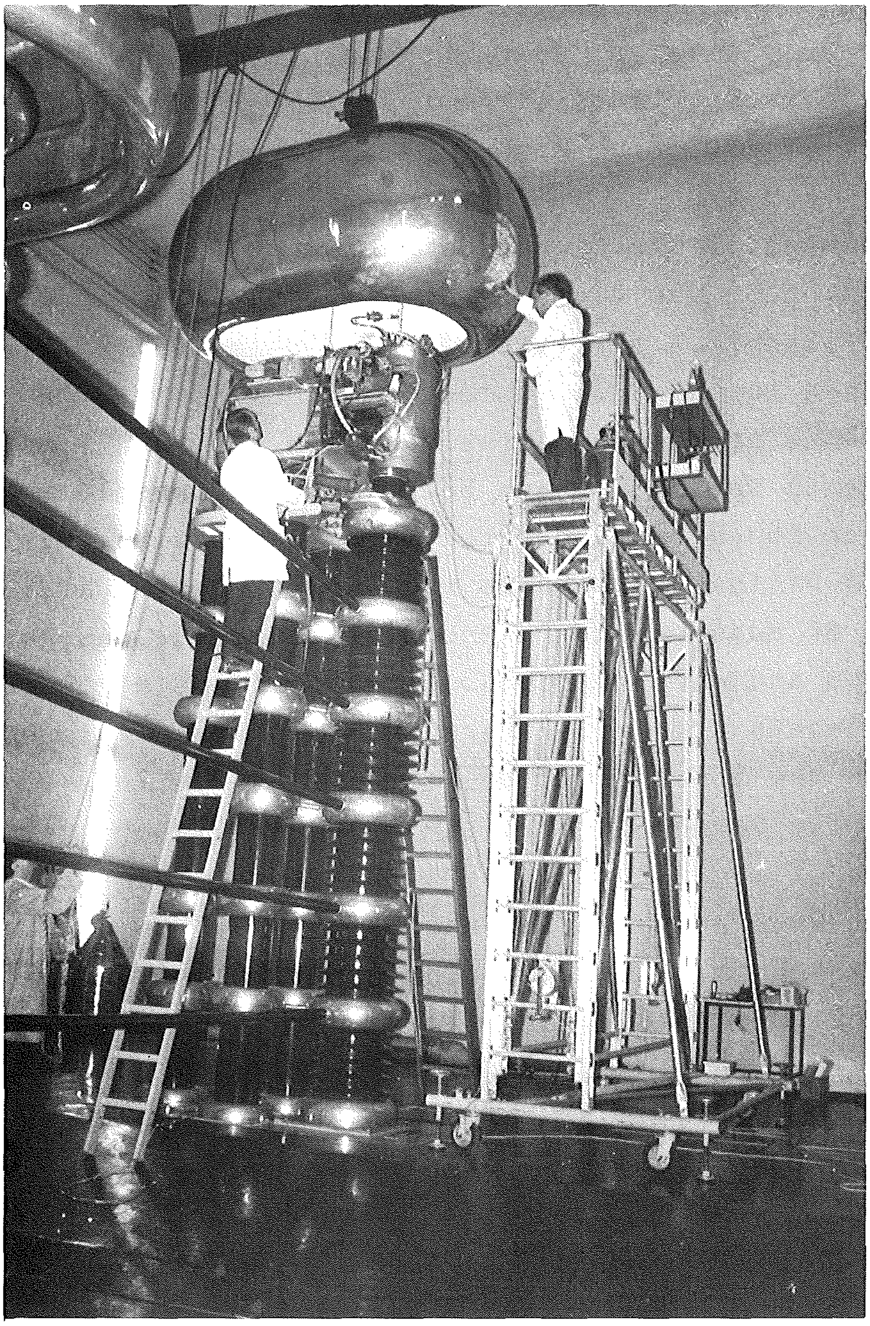

Fig. 5: Experimental set-up for the neutralization experiments at Grafschaft. Underneath the raised high voltage dome of the accelerator the cylindrical cryostat of the cluster ion beam source can be recognized.

3. State of Technical Planning of the Injector Structure

In cooperation with industry the technical feasibility of the injector designs discussed in the basic planning report[1)] was ensured for the version with cluster ion beam source at high voltage potential. This design incorporates the smallest physical risk because drift sections for the neutral particle beam which are located in the electric field are avoided.

In this design the injector structure is best subdivided into three major units (Fig. 6). In order to block as

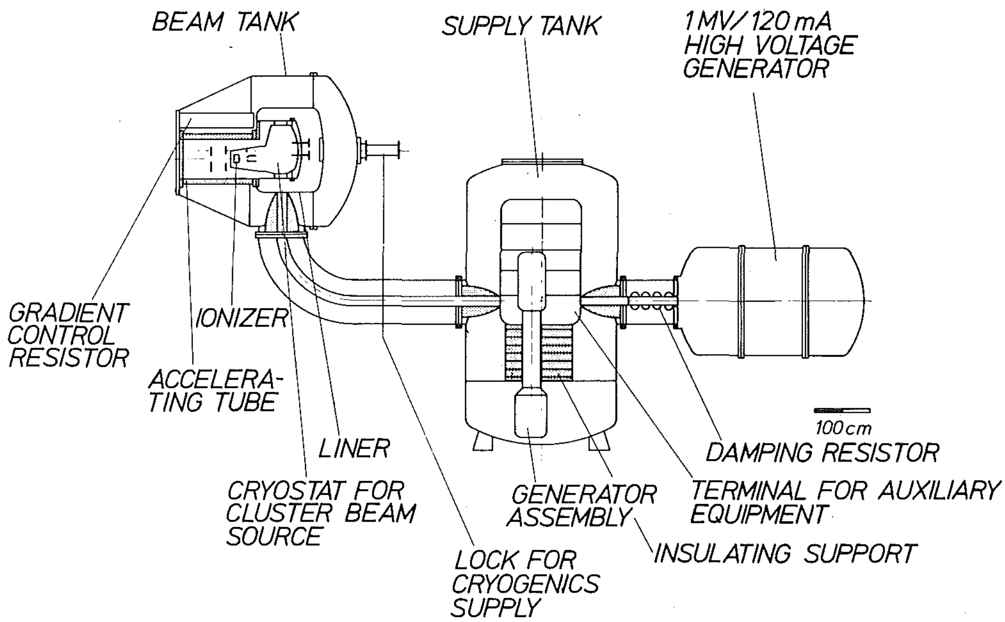

Fig. 6: Schematic representation of the injector structure with the three units of beam tank, supply tank, and high voltage generator.

little space as possible around the plasma experiment the accelerator tube, ionizer, and the cluster beam source surrounded by a liner for field formation are combined in a beam tank which is directly attached via the neutralizer to the injection channel to be built in the Wendelstein VII stellarator. All the supply units of the cluster ion beam source are combined in a separate supply tank connected with the 1 MV / 120 mA high voltage generator. This subdivision makes for a high degree of flexibility in the set-up of the injector. In order to make the structure as compact as possible, an SF_6 gas insulation, which is successfully employed in high voltage technology, at 4 At pressure is used. The three tanks are interconnected by SF_6-insulated 1 MV coaxial lines of 71 cm outer diameter[+)]. The beam tank and the supply tank of the injector are made of non-magnetic material to avoid passive magnetic field disturbances of the plasma device.

An accelerator tube in the CERN technology[20)] is used to accelerate the cluster ions to an energy of 1 MeV (Fig.7). The tube, which is built up of alternate layers of gradient control electrodes and 20 ceramic rings, has a length of 137 cm including the end flanges which are kept at 1 MV high voltage potential and ground potential, respectively. Because of the secondary particle load of the tube caused by the 10 A beam the field strength along the tube is designed to be relatively low, on the order of 8 kV/cm. External spark gaps protect the tube from higher potential gradients. The electrodes are made of a titanium alloy. The high potential gradients of a few

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+) This concept also allows the two beam tanks to be connected to the central supply tank for injection experiments with two opposed particle beams.

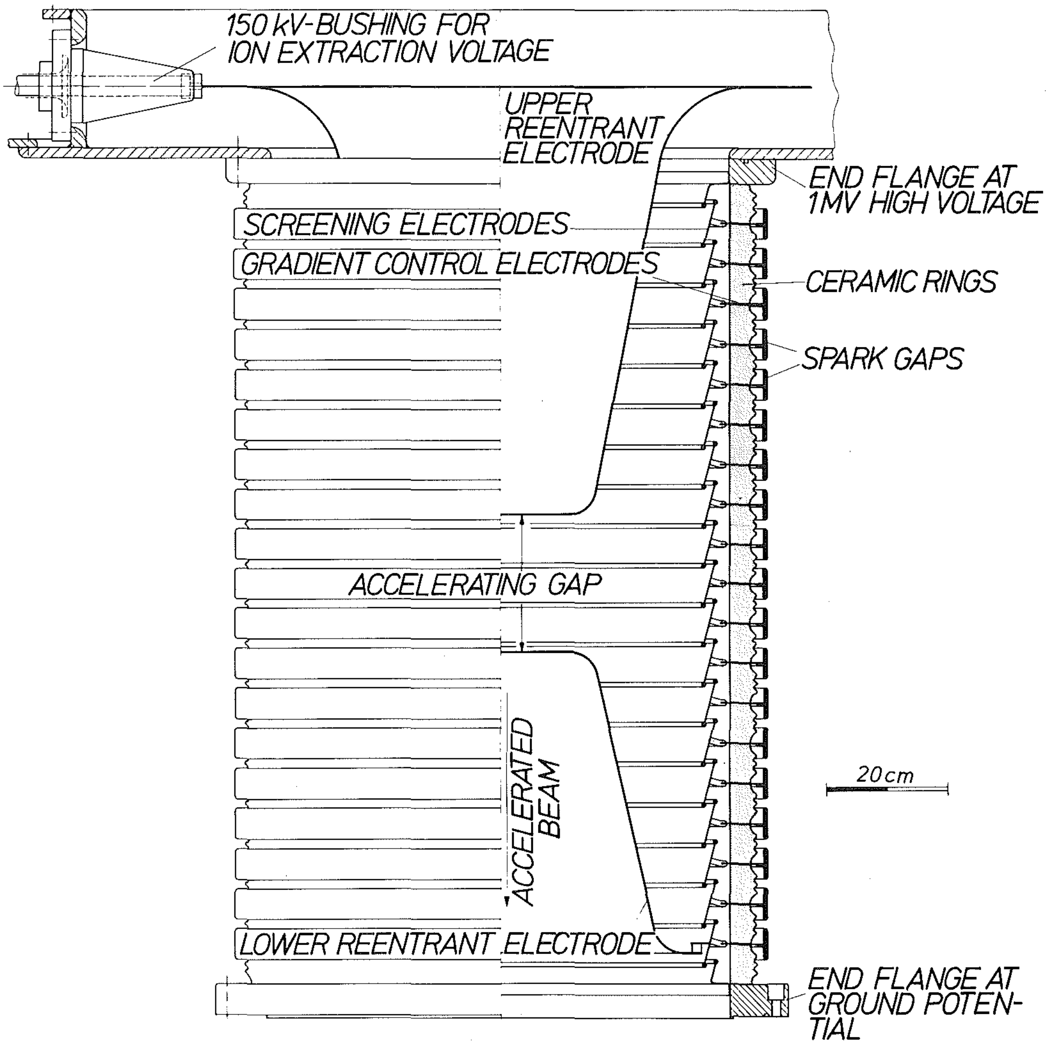

Fig. 7: 1 MV-accelerator tube for the injector.

10 kV/cm planned for the cluster ions in the acceleration gap are achieved by the bell shaped, so-called "reentrant" electrodes leading into the interior of the tube. The upper reentrant electrode accommodates the ionizer and most probably also serves as extraction electrode. Accordingly, it is supplied with the ion extraction voltage through a high voltage bushing designed to 150 kV. Because of the dimensions of the upper reentrant electrode necessary for accommodation of the ionizer the inner diameter of the tube is 75 cm. So far, tubes of this design have been operated with a diameter of 50 cm. The possibi-

lity of increased tendency for electrical break-down due to the larger diameter is regarded by experts as being insignificant.

Estimates have shown that secondary electron currents on the order of mA may occur in the accelerator tube due to cluster-cluster and cluster-background gas collisions. Hence, the gradient control resistor necessary to control the potential gradient along the tube is designed for a current of 10 mA. The maximum thermal power of 10 kW is to be removed by an SF_6 cooling circuit. The cylindrical resistor is installed right by the side of the accelerator tube, as is shown in Fig. 6.

The ion optical system for guidance of the cluster ion beam in the accelerator tube will be prepared by the appropriate work. Preliminary estimates[21)22)] have shown that it should be possible to attain the desired beam properties with relatively simple ion optical devices.

The cluster beam is produced by an expansion of a pre-cooled gas in a nozzle. The necessary cryo-pumping system is cooled by a cryostat[23)] which is filled with liquid helium and insulated by liquid nitrogen (Fig. 8). The volumes of 50 l of liquid helium and nitrogen each are so dimensioned that operating periods in excess of 12 h result for a total active period of some 24 h for beam pulses of 10 sec duration with cycle times of 7 min. These operational data are adapted to conditions in the Wendelstein VII experiment. The cryostat is filled with the cryogenic liquids from the outside by means of a siphon system[+)]. Locks[24)] were designed for refilling which allow

+) A study of the possibility of cooling the cluster beam source by a refrigerator kept at high voltage potential indicated that at the present state of the art such systems could be operated in the interior of a pressurized SF_6 tank only at considerable risk.

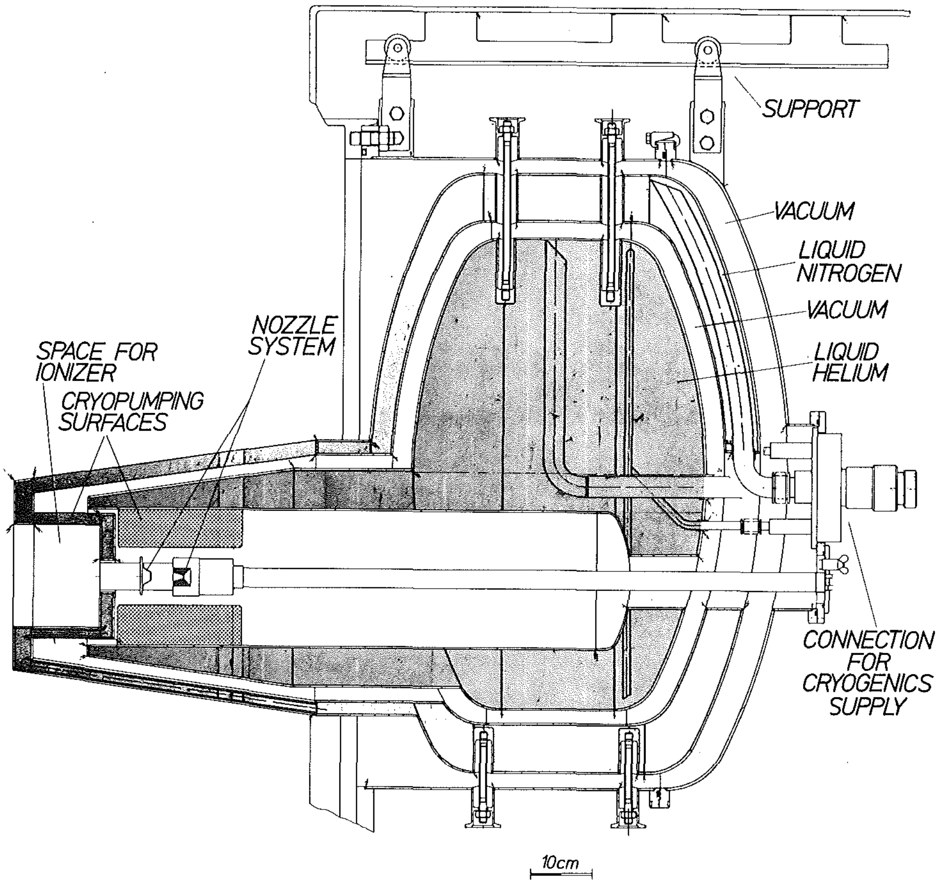

Fig. 8: Draft design of the cryostat of the cluster beam source of the injector.

the liquid siphons to be introduced into the interior of the beam tank through the pressurized insulation gas.

In order to make the shape of the cryostat of the cluster beam source independent of the boundary conditions imposed by the high voltage, to facilitate fabrication and handling, a liner is put around the cryostat as shown in Fig. 6. The liner also contains the disconnecting points of lines connecting the supply tank and the cluster ion beam source. They are used for electricity supply and cooling of the ionizer, measurement and control, and for carrying the exhaust vapor of the cryostat. The disconnecting points are opened by couplings, if the cluster ion beam source is detached from the accelerator tube for repair or maintainance and withdrawn from the beam tank through the rear opening. The beam tank and the liner can be opened through appropriate lids.

The extension of the cryostat which is inserted into the upper reentrant electrode of the accelerator tube surrounds the ionizer as a cryopumping surface, the ionizer being directly attached to the beam generation system of the cryostat. This cryopump at the same time has suction openings towards the accelerator tube.

The high voltage terminal of the supply tank shown in Fig. 6 contains the electric equipment for the cathode heating, anode voltage and extraction voltage and facilities for removal of the heat produced in the ionizer. In addition, the terminal includes compressors and vacuum pumps handling the exhaust vapor and the transmitters and receivers of a telemetry system. The vertical cylindrical terminal is subdivided into five levels where the supply equipment is installed in layers. It is erected on a hollow cylindrical resistance controlled insulated column approximately 1 m long. The column is made of alternate porcelain rings and gradient control electrodes glued together. The individual levels can be removed in layers through a corresponding flange opening at the top of the tank. In the interior of the tank access to the equipment is possible through a manhole in the sidewall.

The 1 MV lines come in at the bottom level of the terminal; they connect the supply tank with the beam tank and the high voltage generator, respectively. Most probably potential controlled bushings cast of epoxy resin will be used for connection of the high voltage line to the respective tanks (Fig. 9). These bushings control the field for-

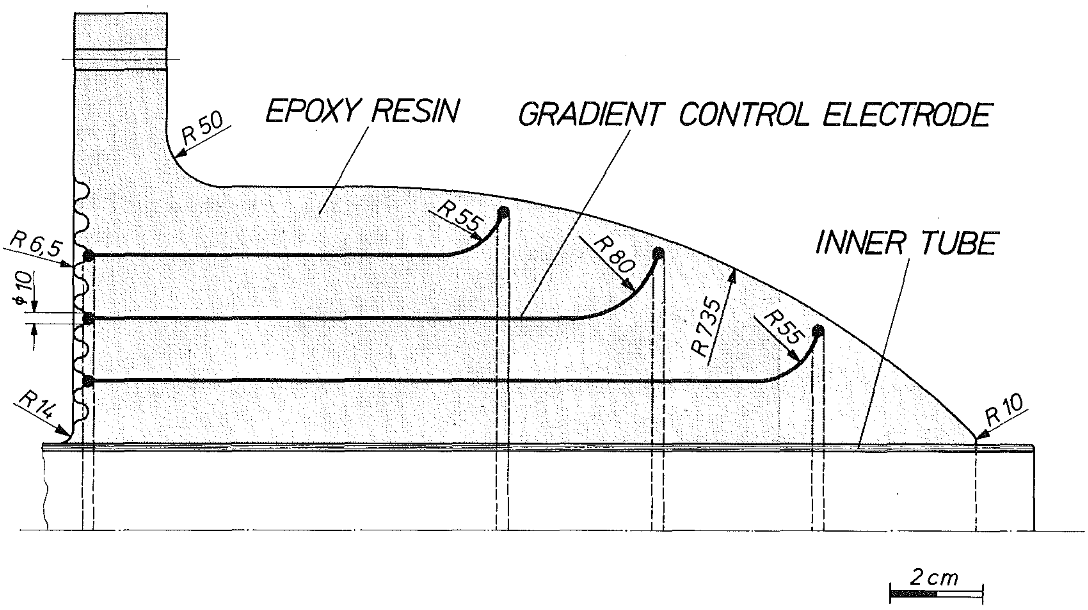

Fig. 9: Potential controlled bushing for a voltage of 1 MV. The tubular inner conductor is surrounded by an insulating body made of epoxy resin whose cast control electrodes determine the potential conditions.

mation at the points of connection and at the same time act as separation wall for the SF_6 volumes, thus allowing each tank to be opened without requiring the large amounts of SF_6 in the other tank to be moved.

Energy is supplied to the terminal by a 40 kVa motor generator. A motor installed at the bottom of the supply tank at ground potential drives a 50 Hz generator in the terminal by means of a vertical insulating shaft running in the interior of the controlled insulation column of the high voltage terminal. The equipment operated in the supply tank and the cooling circuit of the ionizer generate a maximum thermal power of 40 kW in the terminal. This heat is transmitted to ground potential by an SF_6 cooling circuit and passed on to cooling water.

A standard telemetry system operating with light conductors will be used to transmit information for the measurement, control and regulation functions in the high voltage terminal. The bundle of light conductors is run in the potential controlled interior of the insulation column. Parallel mechanically operated control rods will be used for the most important safety circuits.

The helium and nitrogen exhaust vapors of the cryostat of the cluster beam source, of which some 1.5 std.l/sec each will be produced, will first be fed through the 1 MV connecting line into the interior of the high voltage terminal in the supply tank because of the desired small dimensions of the beam tank. In the supply tank, the helium and nitrogen could be discharged to the SF_6-insulation and, during appropriate recirculation, could be separated from the $SF_6/He/N_2$ mixture at ground potential. It is known that N_2 impurities of a few percent do not reduce the insulating capacity of SF_6 at 1 MV[25] to any larger extent. Investigations at lower voltages indicated that a few percent of helium impurities only slightly reduce the insulating capacity of SF_6[26]. Corresponding experimental investigations in the MV range are being conducted. On the basis of 5 % He and 5 % N_2 concentrations in SF_6 the mixture will be withdrawn at a rate of approximately 150 std. m^3/h and reprocessed externally. This cleaning step will be carried out in an expansion of the SF_6 maintainance plant which anyway will be built for pumping off and storage of the total volume of SF_6 of approximately 250 std.m^3.

When constructed the injector will be set up and operated first at IKVT. Fig. 10 shows the preliminary setup in the experimental hall of the IKVT. In this test phase

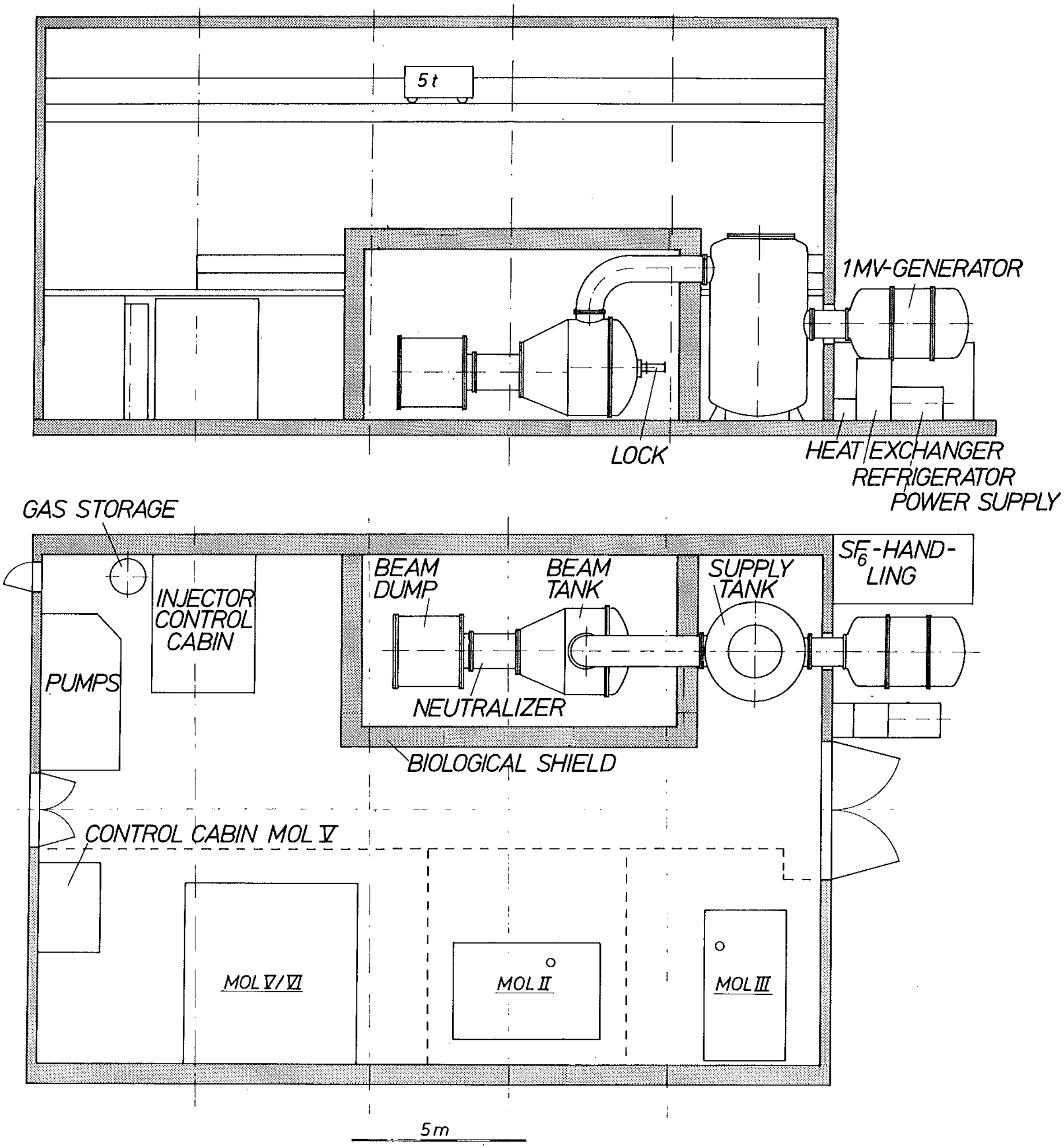

Fig. 10: Preliminary arrangement of the injector in the experimental hall of IKVT.

the accelerated cluster ion beam will be captured in a beam dump[27]. For suppression of the X-radiation produced in the accelerator tube a biological shield made of 60 cm concrete will be built around the beam tank, the neutralizer and the beam dump. If necessary the biological shield can be reinforced.

4. Time Schedule

The time schedule of the project as outlined in this report is evident from Fig. 11. Within the framework of development work performed at Karlsruhe on the cluster ion beam source for particle currents of 10 A a test facility was ordered which will be commissioned by mid-1974. By mid 1976 the cluster ion beam source for the injector schould be finished.

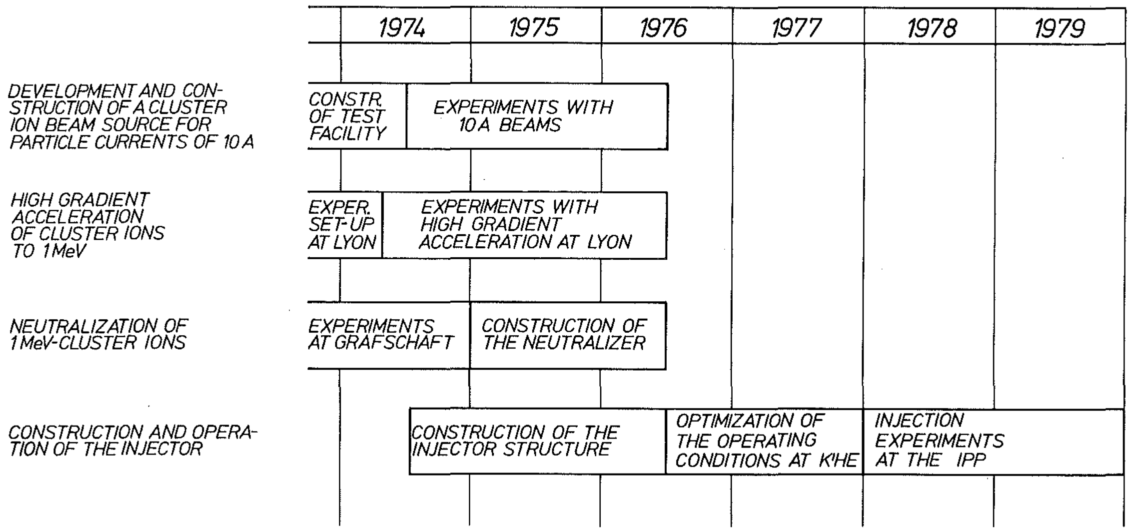

Fig. 11: Anticipated time schedule.

The test assembly for experiments on the high gradient acceleration of cluster ions to 1 MeV at Lyon should be finished by the late spring of 1974. The results of experiments then performed will have a special bearing upon the operation mode of the injector.

Experiments under way at Grafschaft with respect to the neutralization of MeV cluster ions will be continued in 1974. In 1975 the neutralizer for the injector should be constructed.

The construction of the injector structure by industry should be finished by mid-1976, if the order is placed by mid-1974. In the initial operating phase at Karlsruhe up to the end of 1977 the operating conditions of the injector should be optimized for the injection experiments at IPP scheduled for 1978/79.

The time schedule for the total cost of the project is represented in Table 1 for the years 1972-1975 in accordance with the planning estimates included in the R+D programs of Gesellschaft für Kernforschung (GfK), Karlsruhe. The table does not include the personnel costs of three members of the University of Karlsruhe participating in the project. The personnel costs for 1975 were determined on the basis of the personnel costs planned for 1974 without any additional cost increases. The operating phase of the injector anticipated for 1976-1979 can probably be covered by a continuation of the overall cost assessed for 1975.

Year	1972	1973	1974	1975
Total cost, TDM R+D program, GfK	1.777	4.324	2.056	2.140
German FRTP	-	1.490	1.141	1.309

Table 1: Total annual cost of the Fusion Injector Project as estimated in accordance with the R+D-program of GfK. The bottom line shows the cost fraction included in the German Fusion Reactor Technology Program (FRTP) for the years 1973-1975.

The cost fraction contained under item 3.2 of the Fusion Reactor Technology Program (FRTP)[28] of the Federal Republic of Germany is shown in the bottom line.

5. Personnel

On December 31, 1973 the scientific and technical personnel outlined below cooperated in the Fusion Injector Project. The Project should possibly be continued along these lines.

Scientific Staff

Dr. H. Falter
Dr. O.F. Hagena
Dr. W. Henkes
Prof. Dr. R. Klingelhöfer
Dr. K. Körting
DP. F. Mikosch
Dr. H. Moser
Dr. W. Obert
Dr. J. Wüst

Technical Staff

S. Dürr
J. Guérin
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G. Stern

References

1) Das Projekt Fusionsinjektor im Institut für Kernverfahrenstechnik des Kernforschungszentrums Karlsruhe. Planungsgrundlage, Stand Juli 1972. (Unpublished)

2) H.D. Falter, W. Henkes, Plasma Buildup in Toroidal Reactors by Neutral Injection. 6^{th} European Conf. on Controlled Fusion and Plasma Physics, Vol. I, p. 385 (1973).

3) J. Wüst, Aufstellung des Fusionsinjektors am W VII-Experiment im IPP/Garching. (1973) (Unpublished)

4) V. Hoffmann, Untersuchung von H_2-Agglomerat-Bruchstück Spektren mit einem magnetischen Ablenkfeld. (1971) (Unpublished)

5) V. Hoffmann, Ionenquellen. IKVT-Seminar, Wintersemester 1970/71, 4. Referat, 5. Teil.

6) O.F. Hagena, Cluster Beams from Nozzle Sources. Gas Dynamics Series (in the press).

7) O.F. Hagena, W. Obert, Cluster Formation in Expanding Supersonic Jets: Effect of Pressure, Temperature, Nozzle Size and Test Gas. J. Chem. Phys. 56, 1973 (1972).

8) O.F. Hagena, Scaling Laws for Condensation Nozzle Flows. Phys. Fluids (in the press).

9) W. Obert, Experimente mit Wasserstoffclusterstrahlen zur Entwicklung des für die Injektion erforderlichen 10 A_o-Strahls (1973) (Unpublished)

10) H. Falter, W. Obert, Stand der Planung des Ionenquellenteststandes. Interner Bericht (1973) (Unpublished)

11) H. Falter, Abschätzung über den Ionisator (1973) (Unpublished)

12) A. Neugebauer, Planung zur Ausstattung des experimentellen Aufbaus mit Aggregaten und Bauelementen. (1972) (Unpublished)

13) H. Moser, Telemetriesystem (1973) (Unpublished)

14) H. Moser, Diagnostik an beschleunigten und unbeschleunigten Clusterstrahlen (1973) (Unpublished)

15) K. Buchheit, W. Henkes, Wechselwirkung beschleunigter H-Agglomerate mit H_2O-Molekülen im Energiebereich von 25 bis 125 keV/Agglomerat (1965) (Unpublished)

16) K. Buchheit, W. Henkes, Wechselwirkung beschleunigter Wasserstoff-Agglomerat-Ionen mit Wasserdampf im Energiebereich 25 keV bis 150 keV/Ion. (1966) (Unpublished)

17) L.D. Stewart el at., Neutral Beam Injection Heating of Ormak. Proc. of the 3rd Int. Syp. on Toroidal Plasma Confinement, Garching, 26-30 March, 1973.

18) O.F. Hagena, W. Henkes, Clusterionenquelle für den 1 MV-Beschleuniger in Grafschaft (1972) (Unpublished)

19) O.F. Hagena, W. Henkes, U. Pfeiffer, Erzeugung und Nachweis beschleunigter H_2-Cluster. Erste Versuchsergebnisse mit dem Beschleuniger in Grafschaft. (1974) (Unpublished)

20) P. Bernard et al., Proposal for a Higher Energy Preinjector for the CERN P.S. Report CERN/MPS/LIN. 70-11 (1970).

21) H.D. Falter, K. Körting, Ionenoptisches System zur Demonstration der grundsätzlichen Durchführbarkeit der Erzeugung von Clusterionenstrahlen hoher Stromdichte (1973) (Unpublished)

22) W. Henkes, Strahltrajektorien in einem homogenen Beschleunigungsfeld (1973) (Unpublished)

23) W. Obert, Konstruktion eines Kryostaten für die Clusterstrahlquelle des Fusionsinjektors (1973) (Unpublished)

24) J. Palmowski, Durchführbarkeitsstudie für eine die Gasisolierung überbrückende Druckschleuse zum Befüllen des Kryostaten und Ausbau des Strahlerzeugungssystems (1973) (Unpublished)

25) E. Steiniger, Durchschlagverhalten von Luft-SF_6-Mischungen bei Gleich- und Wechselspannungsbeanspruchung. ETZ-A, 86, 801 (1965).

26) J.D. Cobin, Some Electrical and Thermal Characteristics of Helium and Sulphur-Hexafluoride Mixtures. Transactions of the AIEE 74, 318 (1955).

27) O.F. Hagena, Planung eines Strahlsumpfes für einen Clusterstrahl mit 100 KW, 10 A_o.(1973) (Unpublished)

28) Deutsches Fusionsreaktor-Technologieprogramm, Vorschlag der Zentren GfK, HMI, IPP, KFA vom 17.9.1973.