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Progress of the accelerator R&D for the Japanese Hadron Project

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ABSTRUCT

This paper will describe the general idea of the JHP facility, primarily from the accelerator's point of view, and up-to-date results of the research and development on accelerator components. Among others, the R&D on the proton linac has been pursued at the KEK Laboratory since 1987, efforts having been devoted mainly to the development of prototype rf power sources, the rf structure development for the coupled-cell linac and the realization of a 10-MeV linac. The R&D study on the heavy-ion linac has been made at Institute for Nuclear Study, University of Tokyo, primarily on the split-coaxial RFQ linac.

I. INTRODUCTION

The Japanese Hadron Project (JHP) aims at a new research facility for not only neutron scattering but also muon science and unstable nucleus physics. Secondary beams like neutrons, mesons, muons and unstable nuclei are produced with a proton beam of 1 GeV and 200 μA in the JHP.[1)]

To date, in Japan, research of pulsed-neutron scattering and muon science has been done at KEK since 1980, using a proton beam of the Booster Synchrotron of the 12-GeV KEK-PS. This facility provides with a beam of an average current of 6 μA at an energy of 500 MeV. There has been a strong demand for higher intensity for many years.

Physics using short-lived, exotic nucleus beams has brought about growing interests among not only nuclear physics, but also astrophysics, atomic physics and so forth. Spallation reactions from heavy elements bombarded with high-energy protons are preferable for producing a variety of unstable nuclei.

A particular feature of the JHP is that it is a combined project of various disciplines which use hadron beams. Accordingly, the time structure of secondary beams is required to cover a wide range from an ultra-short pulse of 20 ns to the continuous. Hence, we have proposed the accelerator system which is composed of a proton linear accelerator, a compressor/stretcher ring, and a heavy-ion linear accelerator. The layout of the proposed facility is shown in Fig.1.

The source of the proton beam is a linear accelerator of 500 m in length, which delivers a negative hydrogen beam with an average current of 400 μA at an energy of 1 GeV. It operates at a repetition rate of 50 Hz with a peak current of 20 mA and a macro-pulse length of 400 μs. A large fraction of the accelerated beam is transferred to the compressor/stretcher ring, and only a small fraction of the accelerated beam, e.g. 10 ~ 30 μA, is transferred to a production target of unstable nuclei.

The function of the compressor/stretcher ring is to compress a 400-μs long beam pulse delivered from the linac to much shorter one, or to make a continuous beam by stretching the accumulated beam. The rf frequency of the ring is twice as high as the revolution frequency, and two bunches are formed in the ring. The time duration of the bunch is 200 ns in the normal operation. One of these bunches is extracted to the spallation neutron source by fast extraction. The number of protons per bunch will be 1.2×10^{13}, the average current dedicated to the neutron source being 100 μA.

The residual bunch is dedicated to muon(and meson) science. The muon science arena requires an extracted beam of a time structure ranging from an ultra-short pulse to the continuous. In the normal operation, the residual bunch is extracted without any measure with a pulse length of 200 ns. If one needs an ultra-short bunch, it is further compressed with the non-adiabatic bunch rotation technique using rf. When the continuous beam is required, the beam is moved to a specific betatron resonance and extracted over a period of 20 ms with the resonance extraction method.

The production of unstable beams applies the technique of on-line isotope separator. The proton beam of some 10 μA hits a thick target of heavy elements, and spallation products, diffused from inside, are ionized and resolved in mass with a high-resolution mass separator. Unstable nuclei so produced are accelerator to an energy of 6.5 MeV/u with a heavy-ion linear accelerator system.

II. DESCRIPTION OF THE R&D PROGRAM

The most crucial issue in the development of the accelerator system of the JHP is the proton linear accelerator. Therefore, we have been running the R&D study since 1987 in the Accelerator Department of the KEK Laboratory. In parallel to this, a development program has been pursued, at Institute for Nuclear Study, University of Tokyo, on the heavy-ion linac.

The proposed proton linear accelerator is composed of;[2)]

- a negative-hydrogen ion source (50 keV)
- a four-vane RFQ (3 MeV)
- an Alvarez section (150 MeV)
- a high-ß section (1000 MeV)

as shown in Fig.2. The design parameters of the linac are shown in Table 1. The following is a brief description of the proton linac.

A feature of the present linear accelerator is that higher rf frequencies are adopted, compared with the conventional. The RFQ and Alvarez sections will operate at 432 MHz, while many proton linacs so far have been operating in the 200-MHz domain. Taking account of the trapping efficiency across the transition region, the high-ß section will be at 1296 MHz. These choices make it possible to apply klystron amplifiers at both frequencies, which implies much more stable and reliable operation than expected with triode or tetrode amplifiers. In particular, klystrons with specifications close to the present requirement are commercially available in the 400-MHz and 1300-MHz regions. Although common in every accelerator, beam availability should be exceptionally important in the JHP linear accelerator, since the users of the experimental facilities will be a number of small-scale experiments, rather than a small number of big, long-term experiments as in high energy physics.

No working linacs in the above-mentioned frequency domains exist up to date, although test accelerators have been built; e.g. the 400-MHz region at Los Alamos. Therefore, the design must be confirmed in actual models, and experiences in operation of the technical components and their assemblies at their nominal ratings must be gained in advance of making the final design. Hence, we have set the followings as the objectives of the R&D study:

(1) Confirmation of the design, particularly of the low-energy end.
Performance of the whole system is strongly dependent on performance of the front-end. Therefore, the construction of the actual prototype of the front-end of the linac with an energy of about 10 MeV has been exhaustively pursued from the beginning.

(2) Development of the rf structure preferable for the high-ß section.
The high-ß section is the main body of the linac in size and cost.

(3) Development of prototype rf sources at both frequencies with designed ratings.
Stability and reliability in operation of the linac depend on how stable and reliable rf power sources work. Beam availability of the whole JHP facility will be certainly determined by reliability of the proton linac. Thirteen power sources are required for the RFQ and Alvarez sections, and 36 for the high-ß section. In this context, we started the R&D program from fabrication of power sources.

The negative-hydrogen ion source is of a volume-production type. Since an RFQ linac will be placed very close to the ion source, a cusp-field surface-plasma type ion source, which uses cesium vapor and could reduce breakdown voltage in the RFQ, is not preferable, although it has been working stably in the KEK-PS for many years. The volume-production type ion source is primarily free from cesium, and has been believed to be bright.

An energy of 3 MeV has been chosen for the RFQ. Higher energy of the preinjector is preferable for the following Alvarez section. Even with the high injection energy to the Alvarez section, the length of the unit cell at the entrance of the Alvarez section is 25 mm, since the rf frequency is twice as high as the conventional one. Hence, strong focusing will be required, in particular at the low-energy part, and permanent magnet quadrupoles will be used. They can produced a field gradient as high as 185 T/m for a bore radius as small as 6 mm. The RFQ and

Alvarez sections are supplied rf power by 13 klystrons, each of which will deliver a peak rf power of 1 MW.

The high-ß section is made of coupled-cell structures, as usual. The total number of accelerating cells is 3568. They are grouped into 152 tanks, and fed rf power by 36 klystrons, whose peak rf power is 3 MW.

The heavy-ion linac for accelerating unstable nucleus beams is composed of; [3]

a split-coaxial RFQ (to an energy of 170 keV/u)
an IH-type linac (1.4 MeV/u)
an Alvarez section (6.5 MeV/u).

Fig. 3 shows the schematic of the proposed heavy-ion linac.

Unstable nuclei produced in the ISOL ion source have an energy of 1 keV/u. Since the velocity of particles is very slow, the rf frequency of the front-end of the heavy-ion linac will be as low as a few ten MHz. The conventional four-vane type RFQ will become big at these frequencies, hence a special rf structure is necessary to accelerate them. The split-coaxial RFQ(SCRFQ) with four vanes is the one which we have adopted in the present scheme. This accelerator can accept unstable particles of a charge-to-mass ratio down to 1/30. In addition to this main channel, a side channel is conceived in order to accelerate stable nuclei of larger charge-to-mass ratios.

The principal objectives of the R&D study on the heavy-ion linac are the development of the ISOL ion source system and the SCRFQ linac.

III. RESULTS OF THE R&D STUDY

III-1. Development of the front-end of the linac

(1) Volume-production type ion source

A volume source has been developed, since it is thought to be bright and free from cesium, as described before. The final goal of the ion source is a peak current of more than 20 mA with a normalized emittance of 1π mm·mrad. After fabricating a couple of models, we have achieved a current of 20 mA with a reasonable size of emittance.

A recent remarkable finding on the volume source is that introduction of cesium brings about appreciable increase in intensity. In our source, we have observed an increase of intensity; e.g. from 3.5 mA to 13mA[4], by the introduction of a little bit of cesium. The fact that no continuous supply of cesium is necessary in the volume source is quite different from the surface-plasma type ion source, in which a fairly large amount of cesium consumption is needed in order to keep cesium coverage of the converter surface on which negative hydrogens are produced.

We have been making experiments in order to explore the mechanism of negative ion production in the volume source. It has been conceived so far that negative hydrogens are produced through dissociative attachment of electrons to highly-excited hydrogen molecules; $e^- + H_2^* \rightarrow H + H^-$. According to experiments made at KEK, the reaction of H^0 (thermal energy) + e (metal)$\rightarrow H^-$ on the surface of the anode electrode plays an important role in the production of negative hydrogens in the volume source. In this mechanism, cesium decreases the work function of the surface, and the above-mentioned reaction becomes easy to occur.

Mori and his collaborators have been measuring the reaction cross section of the above-mentioned fundamental process.[5]

(2) RFQ linac

The RFQ linac has been recently used as the preinjector to proton and heavy-ion linacs, since it can bunch and accelerate particles with high efficiency. The conventional Cockcroft-Walton accelerators are limited in the practical maximum energy to 750keV,while it is possible to design an RFQ linac of much higher energies. The highest energy so far is 2 MeV, which was achieved in Los Alamos. We have struggled with optimization of the RFQ energy by compromising technical feasibilities of a high-energy RFQ and the front-end of the Alvarez section. An energy of 3 MeV has been adopted. The length of the RFQ becomes 2.7 m, in order to keep the maximum surface electric field less than 1.8 times the Kilpatrick limit. This RFQ is made of vacuum-melt, oxigen-free copper(0.2% of silver added). It is, in general, difficult to fabricate a four-vane RFQ long compared to the rf wavelength (4 times the rf wavelength in this case). In order to examine rf properties of the long RFQ, a cold model cavity, full in size but with no vane modulation and no side tuners, was constructed. We have achieved an intervane distance errors of ± 10 μm, and a longitudinal and azimuthal field uniformity of ± 3.5 % with adjusting only end tuners.[6] It is expected that a more uniform distribution could be obtained if side tuners will be installed.

In general, field non-uniformities arise from geometrical imperfections. If the frequency difference between the accelerating mode and the nearest dipole or higher-order quadrupole mode is small as is the case for a longer cavity, a small amount of imperfection mixes these modes and leads to an appreciable field non-uniformity. This is a reason why mechanical accuracy is much severer for longer cavities.

According to experiences so far, tuning process was complicated even with end tuners only. Actually the field distribution was apt to be affected even with change in ambient temperature. Furthermore, when we go to a high-power model, we must anticipate thermal deformation of the cavity and situation would be much more complicated.

It is quite common in the RFQ cavity to use a measure of stabilizing fields. The most classical way is the vane coupling ring(VCR), as shown in Fig. 4(a). Although it has been known to be effective to stabilize fields in most RFQ linacs operating so far, its mechanical structure is rather complicated and cooling of vane coupling rings is very difficult. Application of the vane coupling ring specifically to high-duty RFQ seems to be unpractical. Hence, main efforts have been devoted to develop a new stabilizing mechanism which is applicable to a high-duty cavity like the present case, and a new stabilizing structure have been devised, which we call as the "π-mode stabilizing loop(PISL)",[7] as shown in Fig. 4(b).

The principle of the PISL is that the total magnetic flux normal to a surface surrounded by a conducting closed-loop is zero. As can be seen in Fig.4(b), the PISL affects mainly the field pattern of dipole modes, while leaving the quadrupole modes unchanged. As a consequence, the introduction of the PISL pushes up the frequencies of dipole modes. The larger the coupling area, the larger the frequency shift. As is easily seen, the VCR has the largest coupling area among possible PISL configurations. The PISL concept is certainly a generalization of the vane-coupling-ring concept.

As MAFIA simulations have indicated, the frequency difference of the nearest dipole mode from the accelerating mode is -14 MHz without any stabilizing mechanism, while it become +80 MHz with an introduction of the PISL. It is important that the dipole modes lie above the accelerating mode. The induced capacitance due to the PISL is several times smaller than that of the VCR. The induced current on the conductor and hence the reduction of Q-value are smaller for the PISL than the VCR, accordingly. Resultant longitudinal variations of the quadrupole field on the beam axis are 0.16 % and 0.38 % for the PISL and the VCR, respectively.

Application of the PISL structure to the cold model which we have already finished is now in progress. Confirmation of the new stabilization mechanism will be made by the end of this year. Based on these studies, a high-power model will be fabricated in FY 1991.

(3) Alvarez section[8]

Before fabricating a high-power model, a 35-cell cold model, 2.6 m long and made of aluminum alloy, was fabricated in order to confirm the design of the front-end of the Alvarez section. As seen in Fig. 5, a field flatness within 1.2 % was obtained without use of post couplers. Measurements have shown that the cavity becomes proof against perturbations when post couplers are used, and that it is the optimum to put the post couplers every other cell.

In parallel with rf property studies on the cold model, we have proceeded with development of fabrication techniques of a high-power cavity. The most crucial is the fabrication of NdFeB quadrupole magnets. NdFeB has an advantage of stronger field strength than SmCo, while weaker against radiation. Hence NdFeB will be used at the low-energy end of the linac, where a stronger field is required. From beam dynamics requirements, the deviation of the magnetic center from the axis must be less than 20 μm (r.m.s.), which predicts a deviation of the beam from the axis of 1 mm. We have already succeeded in fabricating NdFeB quadrupole magnets with the required accuracy.

The fabrication of a high-power model 1.2 m long, which corresponds to an energy from 3 MeV to 5.4 MeV, is in progress. It comprises two separate tanks, involving totally 18 cells. The tank and drift tubes are made of oxgen-free copper (OFC). This model will be finished by March 1991.

III-2. Rf structure development of the high-ß section[9]

Among various rf structures, the annular-coupled structure (ACS) has been pursued for the high-ß section of the JHP linac, since it preserves axial symmetry, which is preferable for mechanical and electrical stabilities, and it has relatively high shunt impedance. The on-axis-coupled structure (OCS) has been used in the TRISTAN electron-positron collider of the KEK Laboratory for many years, and a lot of experience in fabrication and operation of the OCS has been accumulated there. The side-coupled structure (SCS) has been developed and used in LAMPF of LANL, and rf properties have been well understood. The structures of these coupled-cavities are shown schematically in Fig.6.

The idea of the ACS is not new, but there have been no ACS cavities so far, which have been developed up to a level sufficient for practical use. The ACS which was developed in the past was a 'two-slot' ACS. But it is inferior to other coupled-cell structures such as the SCS in many respects, and it has been ignored for many years. Problems of the two-slot ACS are that the TM_{110} mode intrudes into the accelerating passband when the slot orientation is identical in every cell, and that the accelerating mode excites a TM_{210}-like mode in the annular coupling cell, when the slot orientation alternates by 90° from cell to cell, which reduces the shunt impedance of the ACS.

In course of the R&D study, we have found, through computer simulation and model test, that these problems are all cleared up when the number of slots makes four or greater. In particular, the 'four-slot' ACS could be promising for the high-ß structure. As a matter of fact, resonant frequencies of the accelerating mode and the TM_{110} mode separate each other (Fig. 7), and the shunt impedance is fairly good; 42 MΩ/m measured at a coupling factor of 0.05. This is competitive with the side-coupled structure.

In order to check performance at high-power, we have constructed a prototype model of a reduced cell number. Figure 8 show the schematic drawing of the high-power model. It comprises a pair of ACS cavities of five accelerating cells coupled via a bridge coupler.

According to low-level measurements, the unloaded Q-value is 1.9×10^4, which is 79 % of the one calculated with SUPERFISH. Since the reduction of Q-value owing to surface finish and assembling is estimated as around 4 %, a reduction of 17 % might come from coupling slots. Figure 9 is the distribution of the accelerating-field measured on the beam axis. It was sufficiently uniform, and no tuning was necessary.

High-power test has been finished with a peak power of 300 kW, a repetition rate of 50 Hz and an rf pulse length of 300 µs. Except for the pulse length, whose designed value is 500 µs, and which is limited by the pulse-forming network of the power supply, the operating condition is the same as the designed value. Figure 10 shows a result of the first conditioning of the assembled unit. The design value was reached in 10 hours. During conditioning, no light emissions due to discharge or arcing were observed inside the cavity. A plateau at 170 kW is owing to conditioning of the rf window. Once the designed power has bee reached, no aging effects are now observed.

III-3. Rf power source development.

As mentioned earlier, we started the R&D program by designing and fabricating a prototype rf power source for 1296 MHz with the specifications similar to one unit of the coupled-cell linac, since we have thought that the power source is the most critical component of the linac, and that the development of components satisfying the specified rating is urgent. Since the required peak power is 5 MW, the capability of the klystron must exceed 5.5 MW. This power is almost the maximum which is thought technically achievable for the pulse length of 600 µs. The pulsed power supply is a line-type modulator and uses a pulse transformer of step-up ratio of 7. The power source itself has been operating, using a dummy load, with a peak power of 5 MW and a pulse length of 400 µs at a repetition rate of 30 Hz. It has been used for testing the prototype ACS cavity assembly.[10]

The rf power source for 432 MHz has already been designed and started fabrication. It uses a klystron with a modulation anode. The high voltage power supply and the hard-tube modulator for the modulation anode have been finished and assembled in KEK. The klystron is now on order.

Table 2 shows the specifications of these power sources.

III-4. Development of the SCRFQ.

The history of research on the split-coaxial RFQ at INS is long. Arai and his collaborators have developed the SCRFQ since 1984. The particular features of the INS' SCRFQ are that it uses four vanes to generate transverse focusing and longitudinal accelerating fields, and that it applies the multi-module cavity structure, which makes it possible to fix electrodes to the cavity wall with stems firmly.

A proton model of the SCRFQ of a frequency of 50 MHz was fabricated in order to investigate rf properties of this type SCRFQ. Table 3 lists the main parameters of the proton model, and Fig.11 shows the structure of the four-vane SCRFQ. In this model, a mechanical accuracy of vane alignment better than ±0.1mm was obtained, and a good field stability was achieved. Beam acceleration test has shown that the performance on output energy, beam emittance and transmission efficiency was in good agreement with the design.[11)]

After success in the proton model, a prototype model, which works under a high-power condition similar to the final design of the JHP heavy-ion accelerator, has been fabricated, in order to examine cooling efficiency,breakdown problem and to accelerate particle beams under the working conditions. This model is completely the same as the front-end of the JHP heavy-ion linac, except for the acceptable charge-to-mass ratio. Table 4 lists the main parameters of the 25.5 MHz prototype SCRFQ, and Fig. 12 shows the schematic of the prototype SCRFQ.[12)]

The fabrication of the cavity was completed in October, 1989. As results of low-power tests, the uniformity of fields among four quadrants is satisfactory(within ±0.6%). The unloaded Q-value is 6400, which is about 84% of the calculation. In high-power tests, they have achieved an intervane voltage of 110 kV with a peak power of 70 kW. Fig.13 shows a curve of attained intervane voltage as a function of aging time. In this graph, aging time means (operation time) x (duty factor). This data was obtained with a duty factor of 0.6% ~ 3%. The multipactoring levels were overcome after aging time of 140 minutes.

High-power tests are continuing so as to increase duty factor to the designed value of 10%. Beam acceleration test will begin with N^{2+} ions by December 1990.

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2. Y. Yamazaki and M. Kihara, submitted to 1990 Linear Accelerator Conference.
3. S. Arai, et al, Proc. 18th INS International Symposium on Physics with High-intensity Hadron Accelerators, Tokyo,March 14-16, 1990.
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Table 1 Design parameters of the proton linear accelerator.

Energy	1 GeV
Total length	500 m
Average current	400 μA
Repetition rate	50 Hz
Peak current	20 mA
Beam pulse length	400 μs
Rf pulse length	600 μs
Duty factor	3 %

Table 2 Specifications of rf power sources.

A. 1296-MHz rf power source		
Modulator and pulse transformer		
Line-type		
Peak voltage	140	kV
Peak current	107	A
Pulse duration	600	μs
Klystron		
Thomson, TH2104A		
Peak output power	5.5	MW
Pulse duration	600	μs
Repetition	50	Hz
B. 432-MHz rf power source		
Modulating anode/hard-tube modulator		
Output voltage	110	kV
Peak output current	92	A
Pulse duration	600	μs
Nunber of load klystrons	2	
Klystron		
Thomson, TH2134		
Peak output power	2	MW
Pulse duration	600	μs
Repetition	50	Hz

Table 3 Main parameters of the 50-MHz proton model of the SCRFQ.

Frequency		50	MHz
Kinetic energy	2.0	59.6	keV
Normalized emittance		0.3π	mm·mrad
Vane length		2.052	cm
Cavity diameter		0.4	m
Intervane voltage		2.9	kV
Transmission			
(0mA)		85	%
(0.1mA)		76	%
(0.2mA)		62	%

Table 4 Main parameters of the 25.5 MHz prototype of the SCRFQ.

Frequency		25.5	MHz	
Charge-to-mass ratio		>1/30		
Kinetic energy	1.0	45.4	keV/u	
Normalized emittance		0.6π	mm.mrad	
Vane length		2.135	m	
Maximum intervane voltage		109.3	kV	
Kilpatrick factor		2.2		
Minimum bore radius		5.21	mm	
Transmission		(0mA)	92.6	%
(3mA)		61.8	%	
(5mA)		47.4	%	

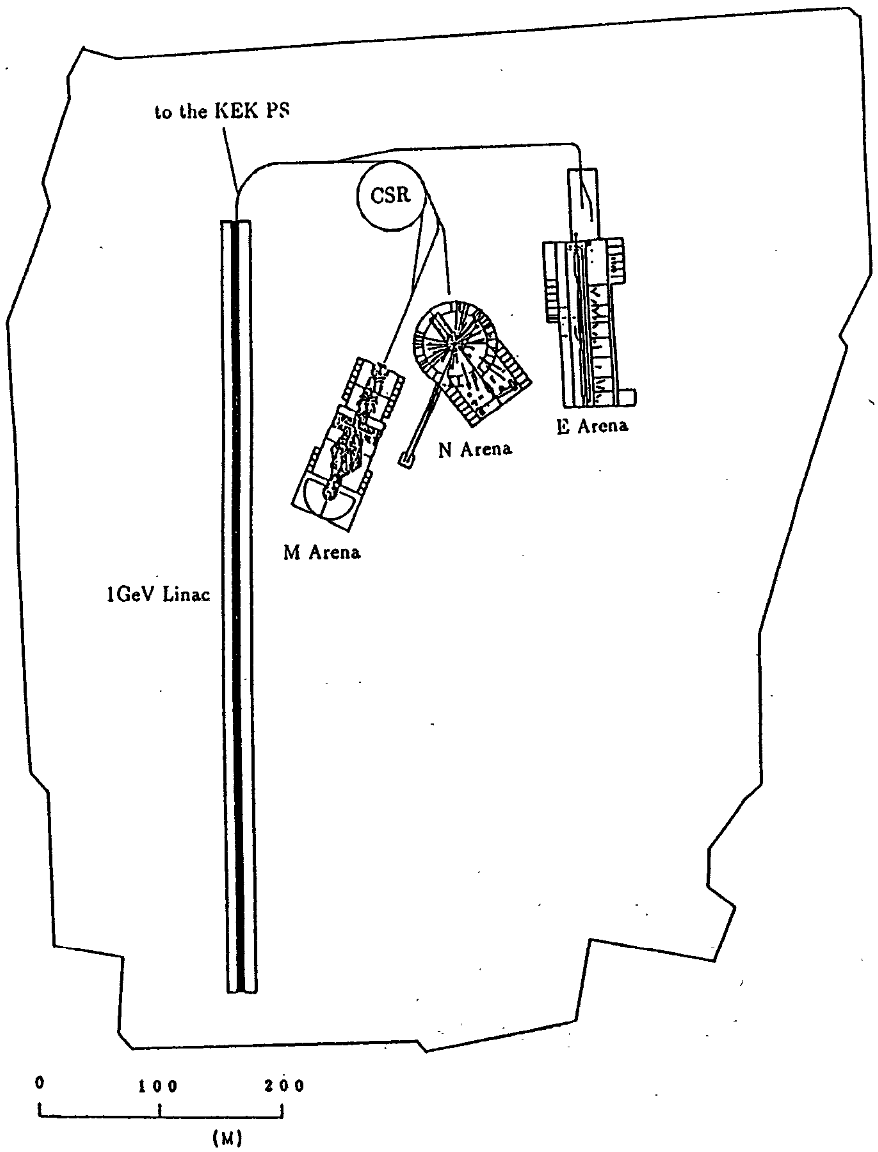


Fig. 1 Layout of the proposed facility of the JHP.

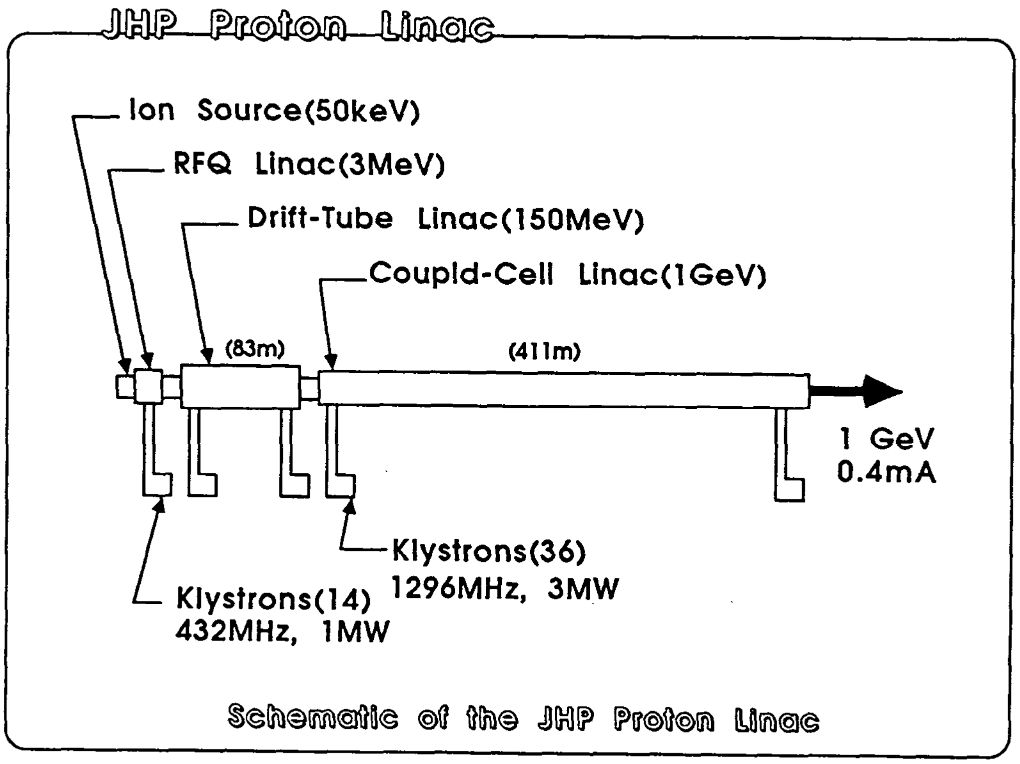


Fig. 2 Schematic of the proposed proton linear accelerator.

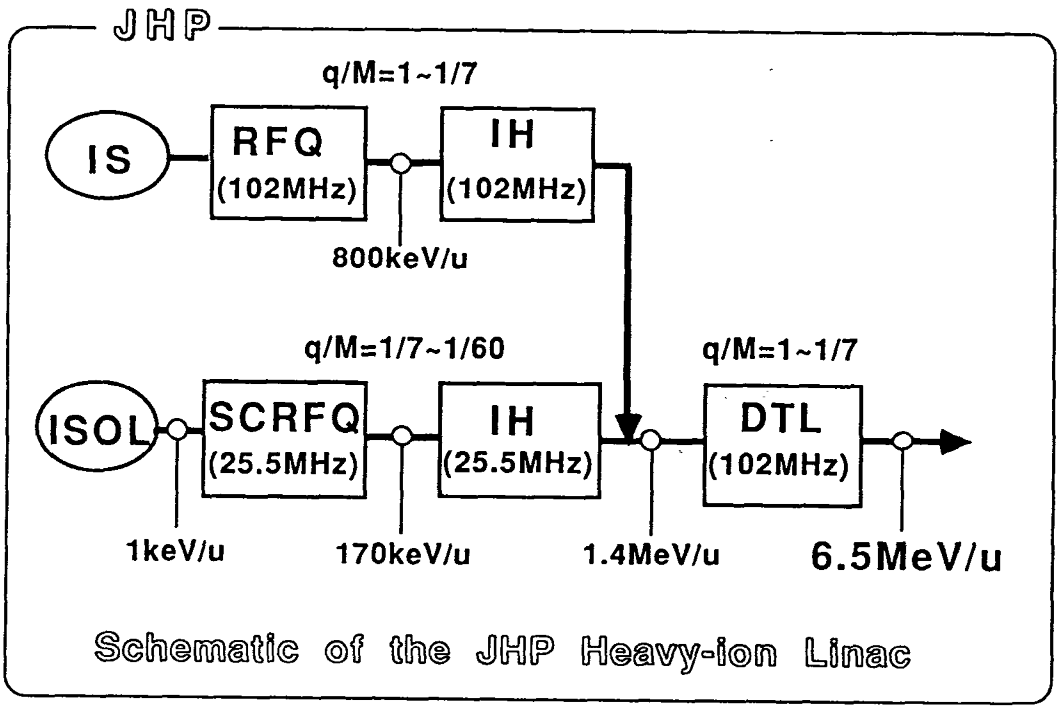


Fig. 3 Schematic of the proposed heavy-ion linear accelerator.

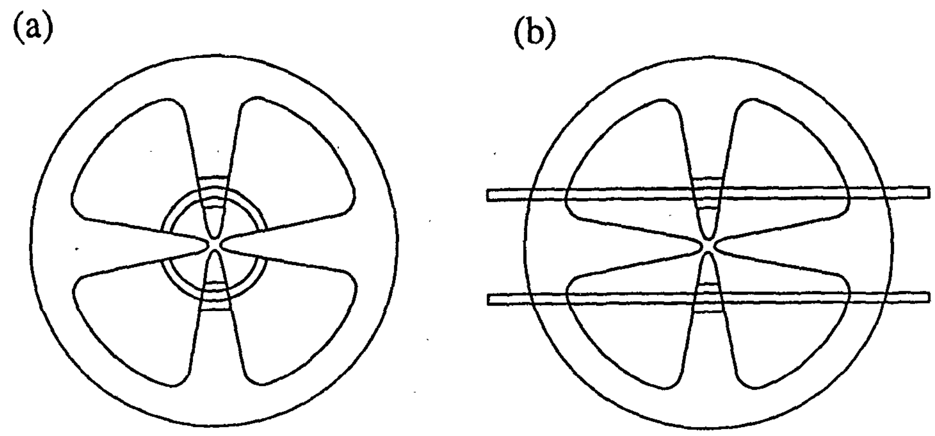


Fig. 4 Field stabilizing mechanisms.
(a) vane coupling ring and (b) π-mode stabilizing loop.

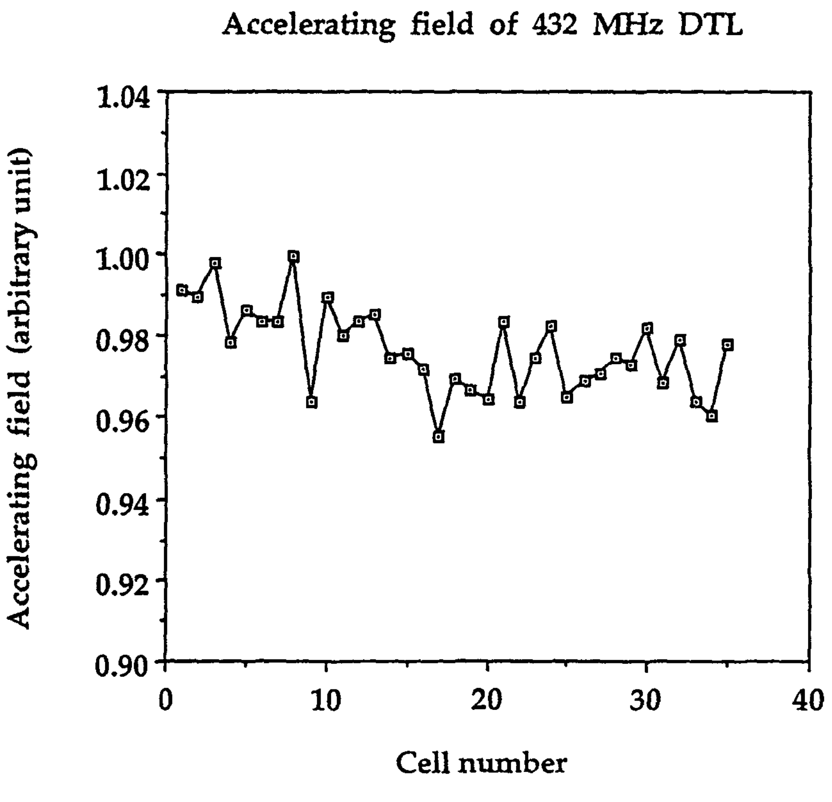
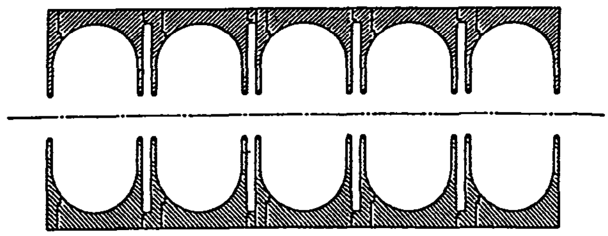
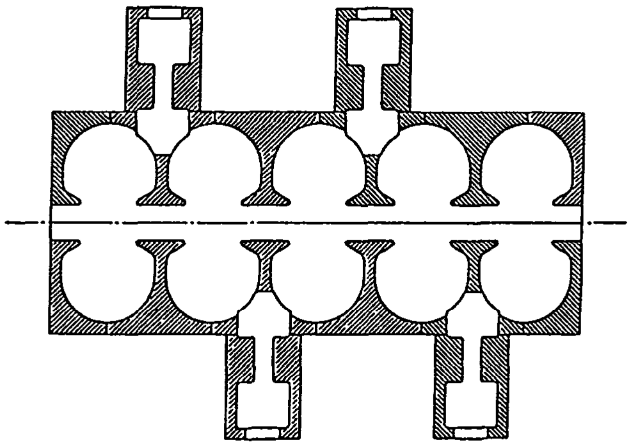


Fig. 5 Field distribution for the 432-MHz Alvarez linac cold model.

On-axis-coupled structure (OCS)



Side-coupled structure (SCS)



Annular-coupled structure (ACS)

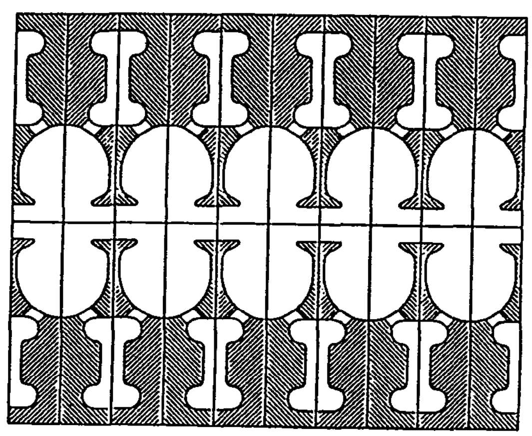


Fig. 6 Various coupled-cavity structures.

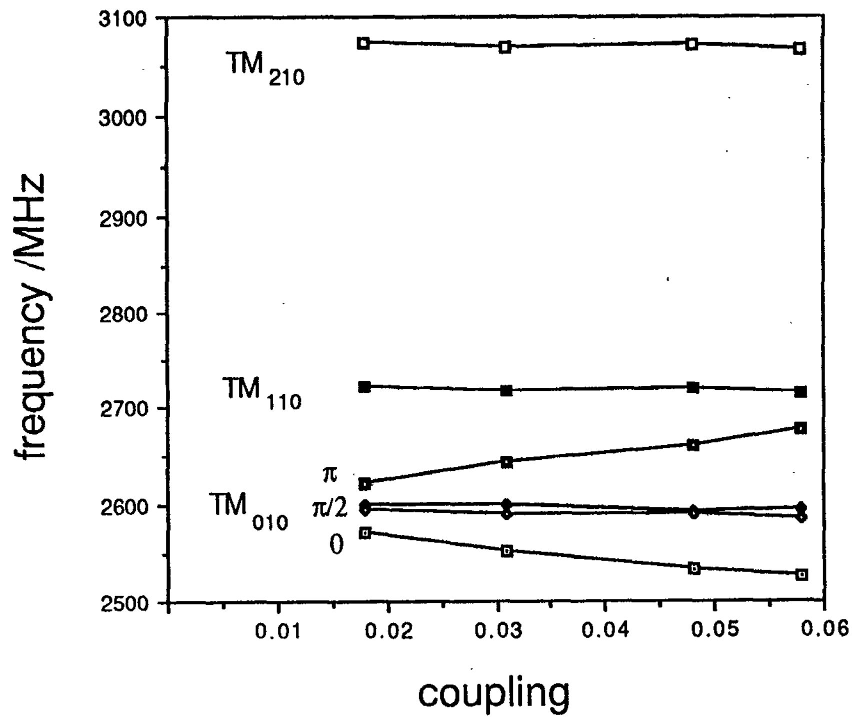


Fig. 7 Resonant frequencies of the accelerating mode and the higher-order modes for the four-slot ACS cavity.

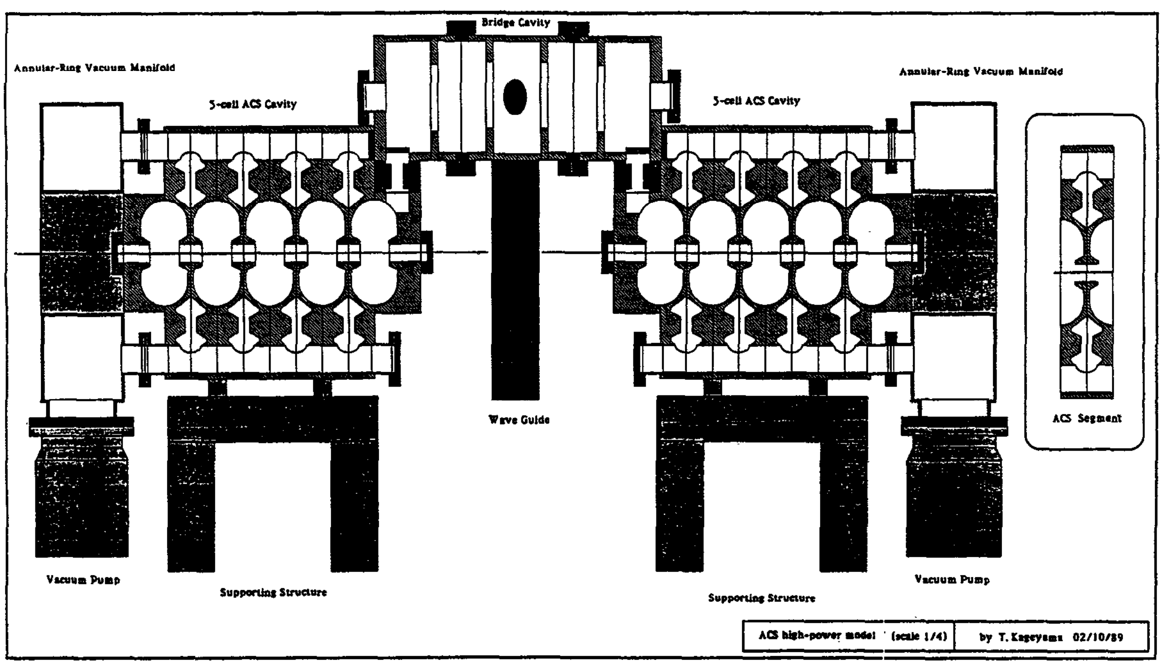


Fig. 8 Schematic drawing of the ACS high-power model.

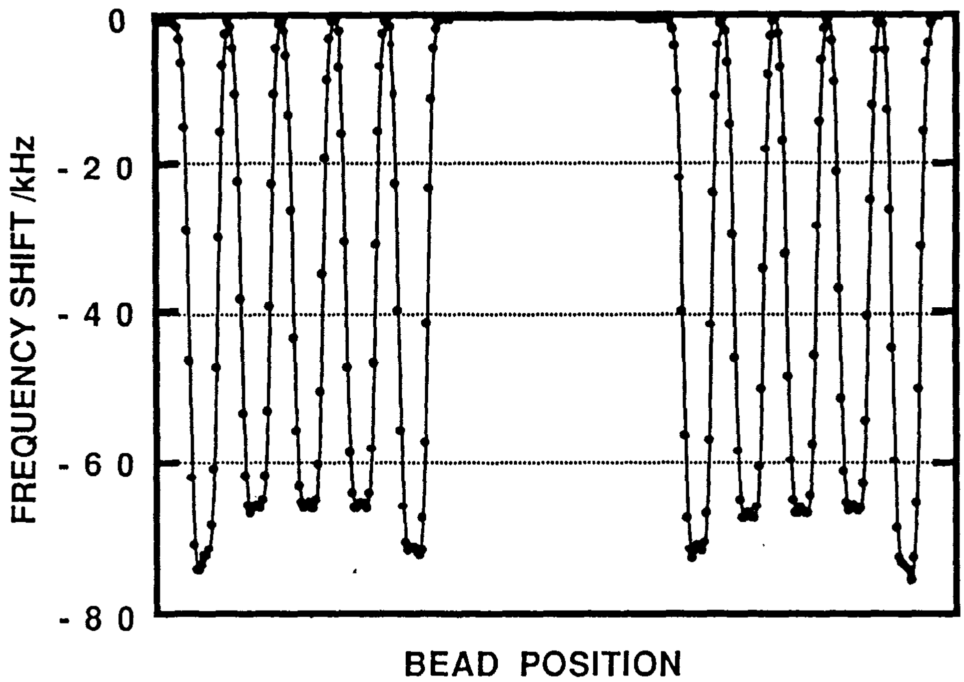


Fig. 9 Field distribution for the ACS high-power model.

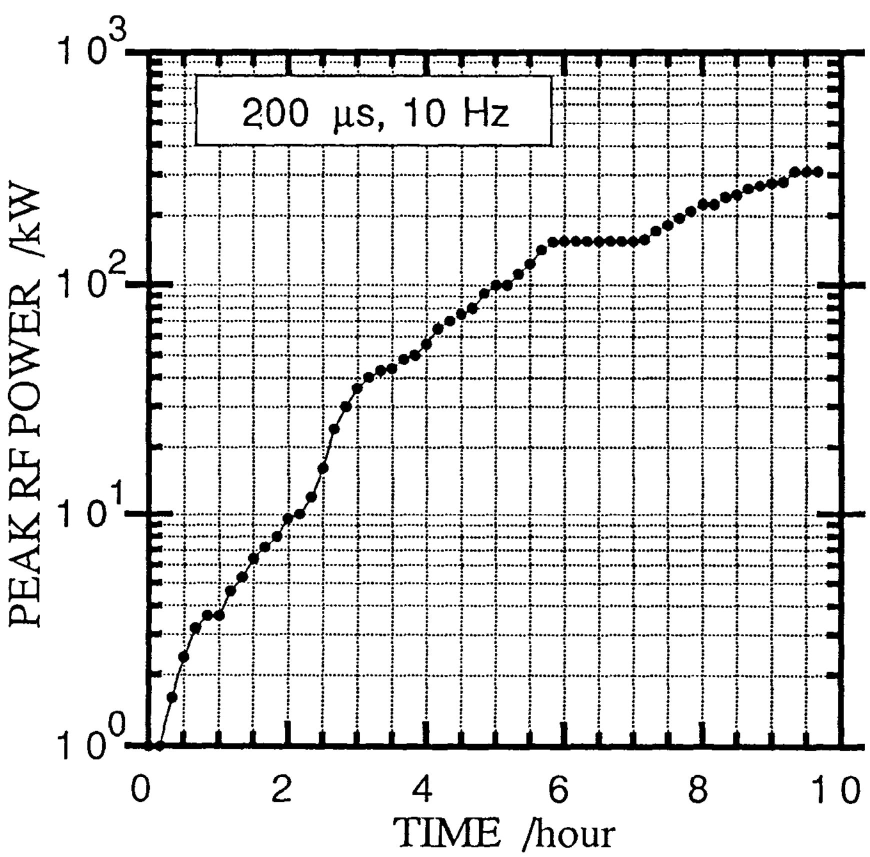


Fig. 10 First conditioning history of the assembled ACS unit.

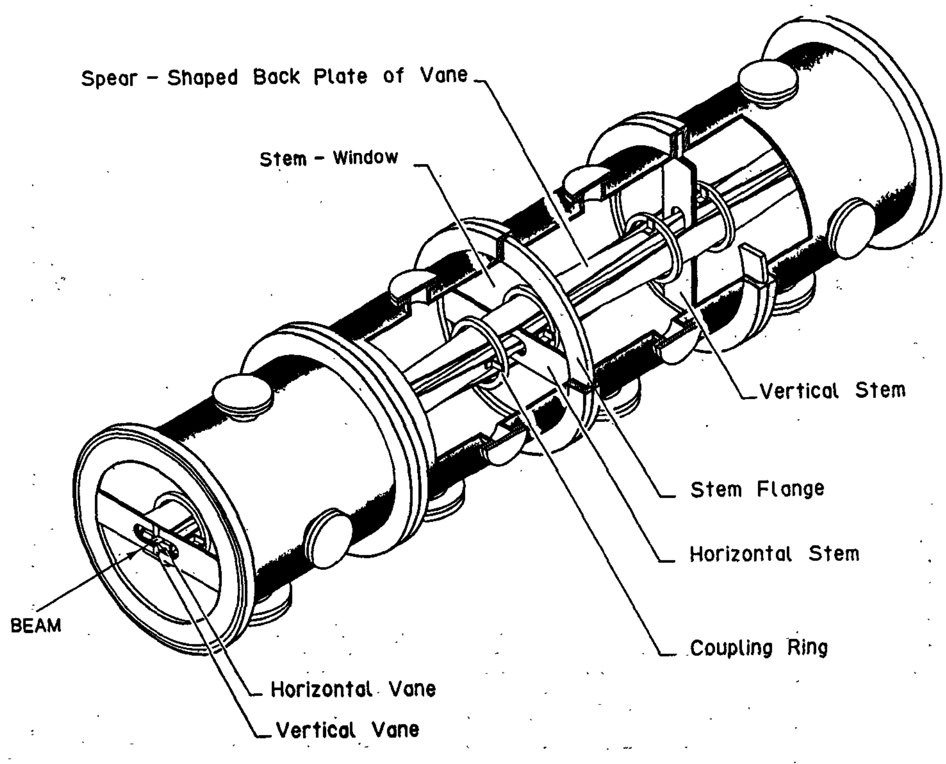


Fig. 11 Proton model of the SCRFQ.

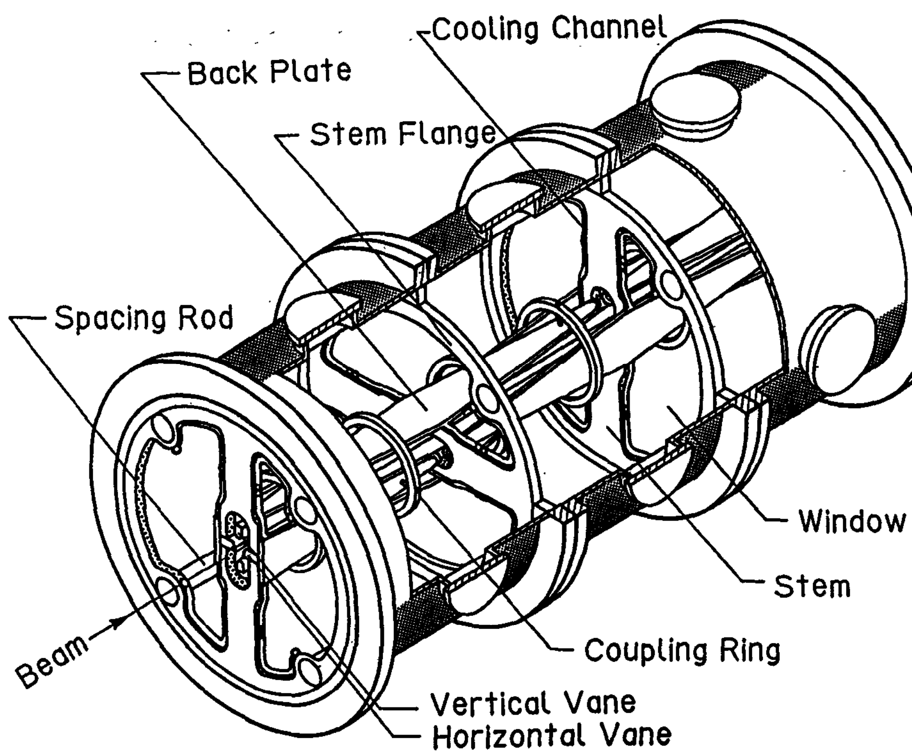


Fig. 12 25.5-MHz prototype model of the SCRFQ.

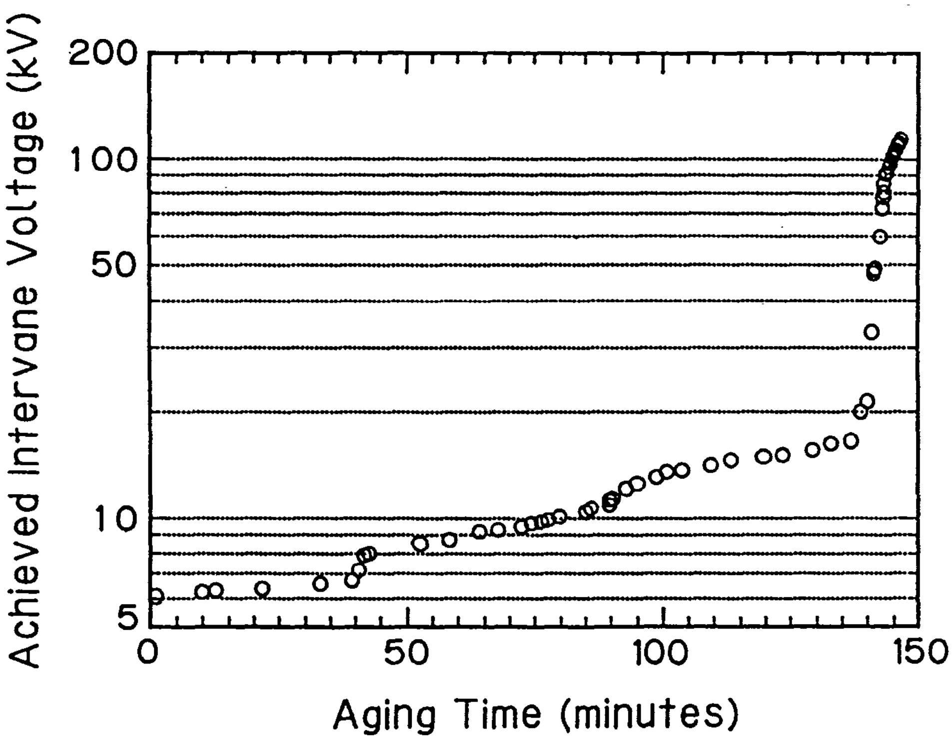


Fig. 13 Aging history of the assembled SCRFQ prototype.

Q(S.Machida): Why do you separate the DTL part of 10MeV into two tanks? I guess there is no advantage.

A(M.Kihara): We make a 10MeV section as one tank. The tank is separated into pieces for technical reasons and assembled together.

Q(A.D.Taylor): Is 400μA a physical or a fiscal limit?

A(M.Kihara): A budgetary problem exists, of course. Technically, more than 400μA is not optimistic in the present design.

Q(I.M.Thorson): What were the considerations that indicated doubling the basic operating frequency for DTL section compared to existing machines?

A(M.Kihara): The main reason is a possibility of using klystrons as power amplifiers for RFQ DTL. It gives rise to stable operation.

Q(R.J.Macek): Are you planning R&D on RF sources?

A(M.Kihara): We have finished a prototype RF source for 1296 MHz with designed specifications. A source for 432 MHz is being fabricated now and will be finished by March 1992.