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REVIEW OF LINEAR ACCELERATORS FOR HEAVY IONS

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Abstract

During the past 5 years there has been a considerable increased interest in ions heavier than were available from existing accelerators ($M \leq 40$, Argon). The requirements for this new generation of accelerators are: ions of all masses through uranium at maximum energies of 8-10 MeV/A with completely variable energies above 2 MeV/A and with energy resolution better than 1/2%. Intensities of up to 10^{12} ions per second are required.

There are presently three heavy ion accelerators in various stages of planning, design and construction, all of which use linear accelerators as a portion of the system. These are the Unilac at Darmstadt, the Helac at Heidelberg, and the SuperHilac in Berkeley.

A brief discussion of these proposed accelerators is presented as well as the present status of these projects.

Introduction

Although there are several promising new ideas for the construction of ions sources capable of producing very high charge state ions, none of these are yet operational, so that the accelerators presently being planned or constructed must be designed to the capability of existing sources. These sources are of the conventional PIG design, operating in a magnetic field of approximately 4 kG, which also serves as a charge state analyzer. There are several modifications to the basic PIG source, generally categorized as the cold cathode, the plasma heated cathode, or the indirectly heated cathode. These variations appear to be comparable in performance for the ultra heavy ions to within a factor of about 2 or so, and are capable of producing acceptable intensities of charge states corresponding to a charge-to-mass ratio $\epsilon \cong 0.045$ ($\epsilon = q/M$).

The velocities that can be achieved with these low charge-to-mass ratio ions with conventional air insulated dc injectors is extremely low ($\beta = 0.008$ at 0.75 MV). Even with the most advanced magnetic quadrupole design, it is impossible to achieve radial focusing at reasonable Alvarez linac frequencies for particles of this charge-to-mass ratio at this velocity. For these ultra-heavy ions, the use of grid focusing is ruled out due to exorbitant power dissipation with even modest beam intensities. The component designed for the low energy portion of the accelerator must therefore utilize a low frequency structure (Wideröe linac), or provide for high energy injection utilizing a dc accelerator. One of the major differences between the three accelerators discussed here, is the method by which the low charge state ions are accelerated to a velocity sufficient to injection into the high frequency linac. The Helac uses a tandem Van de Graff; the Unilac a Wideröe linac, and the SuperHilac a 3 MV Cockcroft-Walton generator.

The requirement for variable energy is also difficult to satisfy in a fixed velocity Alvarez structure. The two Hilacs, at Berkeley and Yale, and the Manchester Linac, have produced variable energies by linearly decreasing the electric gradient along the cavity. At some point in the structure, the synchronous phase angle is reduced to zero, and the particles transit the remaining portion of the system without energy gain. This technique is extremely difficult to tune, and the exiting particles have three or four descrete energies, corresponding to particles falling out of phase in adjacent gaps. The energy resolution is also degraded by a factor of about three, and the RF structure is attenuated. [illegible]r the new generation of heavy ion accelerator, this method of energy variation is considered unacceptable.

The solution to the problem of producing variable energy with a linear system is the use of the multiple short, individually excited cavities. Fortunately, for the heavy ions, variable energy is required only over a limited range, above about 2.5 MeV/A. The system can, therefore, consist of conventional multiple cell Alvarez cavities to a relatively high energy. The short cavities, which can either accelerate or decelerate, can be used as verniers. The systems described here all use this technique, with the single gap cavities of the Unilac providing the maximum flexibility.

Helac

The use of a helical wave guide as an accelerator was first proposed by Walkingshaw, et. at., in 1948. At that time, before the advent of strong focusing, the problems of providing radial stability appeared insurmountable as well as the achievement of reasonable accelerating fields without breakdown of the helix support elements. Recently (1968), however, H. Klein and his associates at Frankfurt have constructed a 1 m long helix section which has been operated with integrated accelerating gradients in excess of 1.5 MV (Fig. 1a, 1b). Moderate strong focusing elements situated between sections of this dimension provide adequate radial stability.

The helix structure provides a low phase velocity in a system of very modest dimensions. It consists of small diameter helix positioned concentrically in an outer vacuum cylinder. In Klein's configuration, power is fed through a insulating seal to one end of the helix, with the other end shorted to the outer wall. The system thus operates with standing waves, the nodes of which can be utilized for stand-off insulator supports for the helical conductor. The phase velocity of the standing waves can be adjusted by varying either the pitch angle or the diameter of the helix.

A large fraction of the total RF power is dissipated on the helix, which consists of copper-plated thin-wall stainless steel tubing, through which water is circulated. The problem of providing the necessary cooling, however, places practical limits on the minimum pitch angle and thus the minimum phase velocity that can be achieved. With reasonable electric gradients at 100 MHz, the device is applicable for particles with energies greater than about 1 MeV/A. The helical linac, when used for the heavier ions, must, therefore, be provided with a relatively high energy injector.

The accelerator consists of several of these short helical sections, with magnetic quadrupole doublet lenses between each (Fig. 2). The phase velocity is adjusted in each of the sections to correspond to the mean velocity of the lowest charge-to-mass ratio particle to be accelerated at that point in this system. For these relatively short sections, the integrated accelerating fields are maximum for the designed velocity (particle velocity equal to the phase velocity), but can be used to accelerate particles over a relatively wider range of velocities, particularly for higher velocities. By maintaining proper RF phasing of the individual sections, the system can thus achieve higher energies for high charge-to-mass ratio particles.

The Helac proposed for construction at Heidelberg utilizes the existing Van de Graff tandem accelerator as an injector. Negative ions are gas stripped in the 11.5 MV terminal and are again stripped before injection into the Helac at a maximum energy of 11.5 (1 + q_s) MV (q_s is the charge achieved by stripping in the terminal). Sixteen 1 meter long helix sections (total length of 25 meter including quadrupoles) operating at 108 MHz with accelerating fields varying from 1.1 to 1.5 MV/m provide a total accelerating potential of 19.2 MV with a synchronous phase angle of 30°. The phase velocities are adjusted for the acceleration of a minimum particle charge-to-mass ratio of 0.26 with an entrance velocity corresponding to that achieved by a Bromine ion stripped to +7 in the 11.5 MV terminal, viz., 1.136 MeV/A. For these particles the Helac sections produce an energy gain of about 5 MeV/A. The maximum energy for particles which will strip to a higher charge-to-mass ratio at the injection energy of 1.136 MeV/A, are shown in Fig. 4.

The minimum charge-to-mass ratio acceptable corresponds to the equilibrium charge state of foil stripped Bromine, so that the system will provide energies above the Coulomb barrier for particles at least to mass 80. Higher energies can be easily achieved by the addition of more helical sections.

Table I
Parameters for Helix Accelerator

Injector MP	
Terminal voltage	11.5 MV
Charge state (terminal)	7^+
Final energy of Bromine	1.136 MeV/Nucleon
Helix postaccelerator	
Injection energy	$\geq$ 1.136 MeV/ Nucleon
ϵ_{min}	0.26
Final energy (Bromine)	6.12 MeV/Nucleon
Number of sections	16
Length	25 m
ΔU	19.2 MV
Frequency	108.48 MHz
Synchronous phase	30°
RF-power (CW)	1.14 MW
Accelerating field	1.1 - 1.5 MV/m
Focusing	Magnetic quadrupoles, doublets, N=1
Radial acceptance (norm.)	1.5 cm mrad
Magnetic field gradients	1.4 - 2.4 kG/cm
Energy spread $\Delta T/T$	$< 1.10^{-2}$
Energy spread with debunching	$< 1.10^{-3}$
Fine structure of beam	< 1 nsec
Energy variation (continuously)	1.136 - 6.22 MeV/Nucleon
Radius of outer conductor	12.5 cm
Radius of helix	3.0 - 2.0 cm

Although the helix is not as versatile as the single gap cavities of the Unilac, described below, it is, by comparison, small, simple and inexpensive. The independently excited cavities provide for extremely flexible operation. Continuous energy variation up to the maximum energy is possible, by successively exciting the sections, using the last section as a vernier. Under these conditions, subsequent sections can be used for bunching or debunching. The combined tandem-Helac can thus provide a completely variable energy from zero up to maximum energy.

Table I shows the various parameters of the presently proposed accelerator and the anticipated performance for Bromine.

This accelerator is presently in the final design, cost estimating phase, which is expected to be completed late fall 1971. If construction proceeds immediately, as anticipated, beams can be expected in mid-1972.

The Unilac

A new heavy ion laboratory is being built in Darmstadt, Germany, with the Unilac as its primary accelerator. This accelerator will be the first in the new generation of systems designed specifically for the acceleration of ions of all masses. It will consist of four separate types of accelerators: a low energy dc injector, four Wideröe prestripper linacs accelerators, two Alvarez poststripper linacs, and a series of 22 independently excited single gap cavities.

The Alvarez and single gap cavities are designed to operate at a frequency of 108 MHz, a frequency for which considerable design experience is available in Europe. The Wideröe prestripper cavities operate on the 1/4 sub-harmonic, 27 MHz. The Wideröe is designed to accept particles with a minimum charge-to-mass ratio of 0.045 with a very low injection potential of 250 kV.

The Wideröe linacs are coaxial line structures (Fig. 5). Although this structure has a somewhat lower shunt impediance than the twin line, the quadrupole lenses are contained in alternate drift tube all of which are attached to the cavity wall, providing a very ridged support and allowing for quadrupole alignment from outside the vacuum cavity. To provide the necessary length for the required quadrupole lenses (5.5 cm pole length with a 2.1 cm aperture), the low energy portion of the Wideröe is arranged in alternate $1/2\ \beta\lambda$ - $3/2\ \beta\lambda$ cells with the quadrupoles located in the longer drift tube. At higher velocities, the system reverts to the normal $1/2\ \beta\lambda$ cell, where quadrupoles of the required strength can be fit into these lengths. Four separate Wideröe cavities with a total of 130 gaps accelerate the particles from $\beta = 0.005$ to 0.054 (1.4 MeV/A).

Gas stripping of uranium at this energy will produce a mean charge-to-mass ratio of approximately 0.1. The poststripper section is therefore designed to accelerate this minimum ϵ.

The stripper area is to contain a magnetic charge state analyzer system to allow selection of a single charge state from the stripped charged state distribution. The thirteen meter drift space between the pre- and poststripper accelerator sections also makes possible the use of an energy bunching cavity at this point.

The poststripper accelerator consists of two 108 MHz Alvarez cavities of conventional design, and a series of 22 single gap cavities with individually tunable RF phase and amplitude. For these latter cells the synchronous phasing can be established for particles of any velocity, so that completely variable energy is possible.

The cavities, shown in schematic as Fig. 6, are designed to provide reasonable transit functions for the slowest particle expected ($\epsilon = 0.1$); for particles with higher charge-to-mass ratios the transit function increases. The 22 single cell cavities can be operated with integrated electric gradients of approximately 1.5 MV each. By proper phasing of the cavities, all of this electric field (times the transit factor) is available for acceleration of particles, independent of their velocity. The energy gained in this portion of the accelerator is thus proportional to the charge-to-mass ratio of the particle. For the designed minimum charge-to-mass ratio, $\epsilon = 0.1$, of the Alvarez section, the energy gain of the single gap cavities is 2.7 MeV/A, and ranges to approximately 30 MeV for protons with $\epsilon = 1$. By proper phasing of these cavities a completely variable energy from the stripper energy of 1.4 MeV/nucleon to the maximum energy can be achieved.

The system as designed provides for extreme flexibility in operation. Adequate drift space has been provided for buncher or de-buncher gaps at various points along the accelerator. As noted above, the poststripper Alvarez cavities have been designed for the mean charge state of uranium with a gas stripper. The use of a foil to produce higher charge-to-mass ratios of this ion makes possible an increased energy gained in the single gap cavity. A foil can also be introduced immediately proceeding the single gap cavities, providing a further increase in maximum energy for experiments where a second stripper intensity loss can be tolerated.

A completely new laboratory is being built for this machine and the construction and installation of the accelerator must await completion of the new building. Ground breaking for the laboratory buildings are scheduled for autumn 1971, with the accelerator tunnel scheduled for completion in October 1973.

The accelerator is in the advanced stages of design. A prototype model of the single gap cavities has been constructed and tested. Gap gradients exceeding 20 MV/meter have been achieved with acceptable sparking rates. A substantial R&D program on other aspects of the system is presently underway, particularly in the design of the Wideröe structures and their quadrupole focusing elements.

Under present scheduling, the construction of the laboratory buildings will determine completion date of the accelerator. First beams are presently expected in late 1974.

SuperHilac

The SuperHilac is a minimum-cost modification to the Berkeley Hilac and is designed to produce beams of all ions to a maximum energy of 8.5 MeV/A. The modified accelerator is designed to use as much of the existing equipment and components as is possible and, in addition, must fit within the existing building. These restrictions, particularly the use of the existing RF amplifiers, drivers and control system which operate on a frequency of 70 MHz, to a large extent dictate the general design of the improved system.

The existing Hilac consists of a 400 kV cockcroft-Walton injector, a 3 m-diameter, 4.5 meter-long prestripper Alvarez cavity with 37 grid focused drift tubes, and a 2.7 meter-diameter, 27 meter-long poststripper Alvarez cavity with 67 quadrupole focused drift tubes. Particles with a minimum ϵ of 0.15 are injected into the prestripper at an energy of 0.073 MeV/A and accelerated to 1.0 MeV/A. The particles are then stripped to $\epsilon \geq 0.33$ and accelerated to a maximum of 10 MeV/A in the poststripper. The maximum mass particle that can be accelerated is 40 (argon) determined by acceptable ion source output and by stripping charge states.

The Alvarez cavities are excited by six RCA type 6949 beam power triodes, one on the prestripper cavity and five on the poststripper cavity. Phasing is maintained between the two cavities to about 1°, using an electronic-phase control system. All of this equipment with minor modification will be used for the improved system.

The prestripper cavity is tuned with a 0.5 m-diameter rotatable loop to the poststripper cavity frequency, which is allowed to drift (approximately 25 kHz) due to thermal expansion under RF load.

The SuperHilac Alvarez cavities will closely follow the design of the original Hilac. Two 3.15 m-diameter vacuum tanks will be used. An 18.5 m-long prestripper with 134 magnetic quadrupole focused drift tubes will accept particles with $\epsilon \geqq 0.045$ and accelerate them to 1.2 MeV/A where they will be stripped to $\epsilon \geqq 0.16$. A three meter long drift space at the stripper is provided for charge-state analysis. The particles are then accelerated to a miximum of 8.5 MeV/A in the 30.9 m-long poststripper, which contains 76 quadrupole focused drift tubes.

For the prestripper cavity with 1 $\beta\lambda$ cell lengths and an aperture of 1.4 cm, the maximum achievable quadrupole strengths is 60 kG (at 14.5 kGLcm) in a 6.5 cm-long cell (5 cm-long drift tube). These parameters determine the entrance velocity at 0.015 c (0.112 MeV/A) for the minimum charge-to-mass particles to be accelerated. The injection potential required is thus 2.5 MV. As an alternative to the low-frequency RF structure necessary to achieve this energy, a pressurized 3 MV shunt-fed Cockcroft-Walton has been designed (Fig. 8). The details of this device are presented elsewhere in these proceedings. The existing Hilac injector, upgraded to 750 kV, will also be used to inject particles with $\epsilon = 0.15$ (up to bromine).

To achieve variable energy, the poststripper accelerator has been divided into separate cavities with 8-13 cells, each of which, when operated at designed electric gradient of 1.8 MV/m, provide a velocity gain of approximately 15%. These cavities, which are indivdually excited with completely variable RF phase and amplitude, can be operated at lower than the designed gradient, in which case the energy gain is approximately proportional to the electric gradient. The five cavities can thus be used to produce a continuously variable energy from 2.5 to 8.5 MeV/A by successively exciting the cavities, using the last excited cavity as a vernier. These cavities are low-cost approach to the single-gap system of the Unilac. In contrast to the single-gap system, however, the multiple-gap cavities degrade the energy resolution by up to a factor of 2.5 when operated in the partial energy mode. It is also not possible to exceed the designed cavity velocity, so that the maximum energy is fixed, even for high charge-to-mass ratio particles.

Figure 10 shows the various parameters of the SuperHilac system.

The two long RF cavities will be cryopumped, using a long 18°K tube running longitudinally along the wall of the vacuum cavities. This line will be thermally isolated from RF with a double-shroud system, the outer operating at 250°K and the inner at 80°K. The system is conductance-limited to speeds of about 2000 liters per second per meter for water and 800 liters per second per meter for other gases condensable at 18°K, providing a total of about 35,000 liters per second per meter for the two cavities. Noncondensables (H, He, Ne) will be pumped with small, heavily-baffled, diffusion pumps, one on each vacuum tank.

The eight separate RF cavities will be tuned to a cold-frequency of 70.2 MHz, using the end gaps and by adjustment of the cryopump outer shround dimension. Subsequent drift of the individual cavities due to thermal expansion will be tuned with rotatable loops, approximately 0.5 m in diameter, located in each cavity.

A study of the dynamics of the particles through the prestripper cavities indicated that, with constant quadrupole strengths, radial stability can be achieved for particles with charge-to-mass ratios varying over a factor of three ($0.045 \leq \epsilon \leq 0.15$). The twin injector system is therefore being designed to allow the injection of particles from each of the injectors on alternate pulses at a 40/second rate. A fast-switching magnet (5 ms rise) will alternately direct particles from the injectors into the prestripper, and a similar switching magnet at the exit of the poststripper will direct the difference beams to different experimental areas. Two simultaneous experiments can thus be carried out with the accelerator, or the complete tuning of the machine for one particle can be accomplished using a small fraction of the beam time, while an experiment is being carried out with another particle using the major fraction of the beam time.

A detailed discussion of this mode of operation of the system is presented elsewhere in these proceedings (F. Selph).

The construction of the SuperHilac is presently underway. The Hilac has been dismantled and necessary modifications to the building are now being carried out. The fabrication of most of the components of the SuperHilac cavities is complete and installation of these will commence about March 15. RF tests of the cavities are expected to commence in September with first beam tests in October using the low-voltage injector with light ions. Tests with the heavy ions will commence later in October. A six-month debugging period is anticipated, with limited beam time scheduled for research during this period. The full research schedule is expected in the spring of 1971.

References and Acknowledgements*

*This work was done under the auspices of the Atomic Energy Commission.

The descriptions of the various accelerators contained here are necessarily brief. More complete details on the use of the Helix structure as a heavy ion accelerator is presented by H. Klein, et. al., in the Proceedings International Conference on Reactions Induced by Heavy Ions (July 1969, Heidelberg). The Unilac is described by D. Böhne in the same Proceedings.

The SuperHilac project is described by the author in UCLRL Report 19919. Photographs and information on the present status of the projects were obtained from J. Klabunde for the Helac, and from D. Böhne for the Unilac.

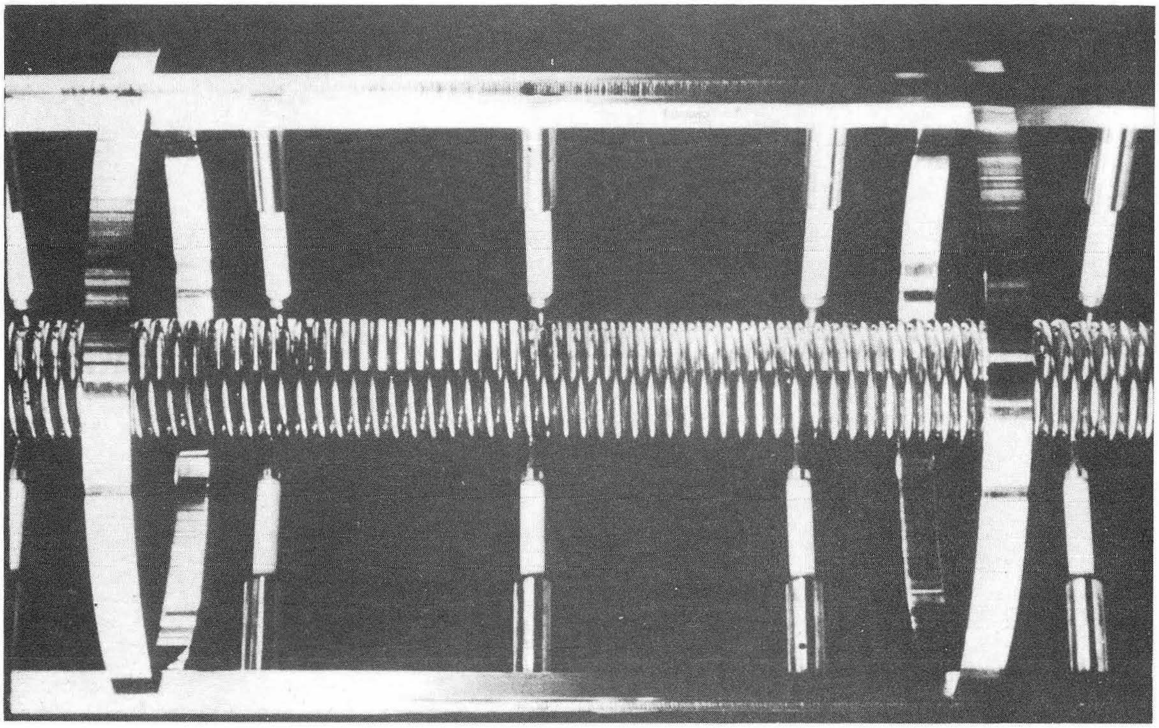

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Fig. 1. Helical accelerator prototype.

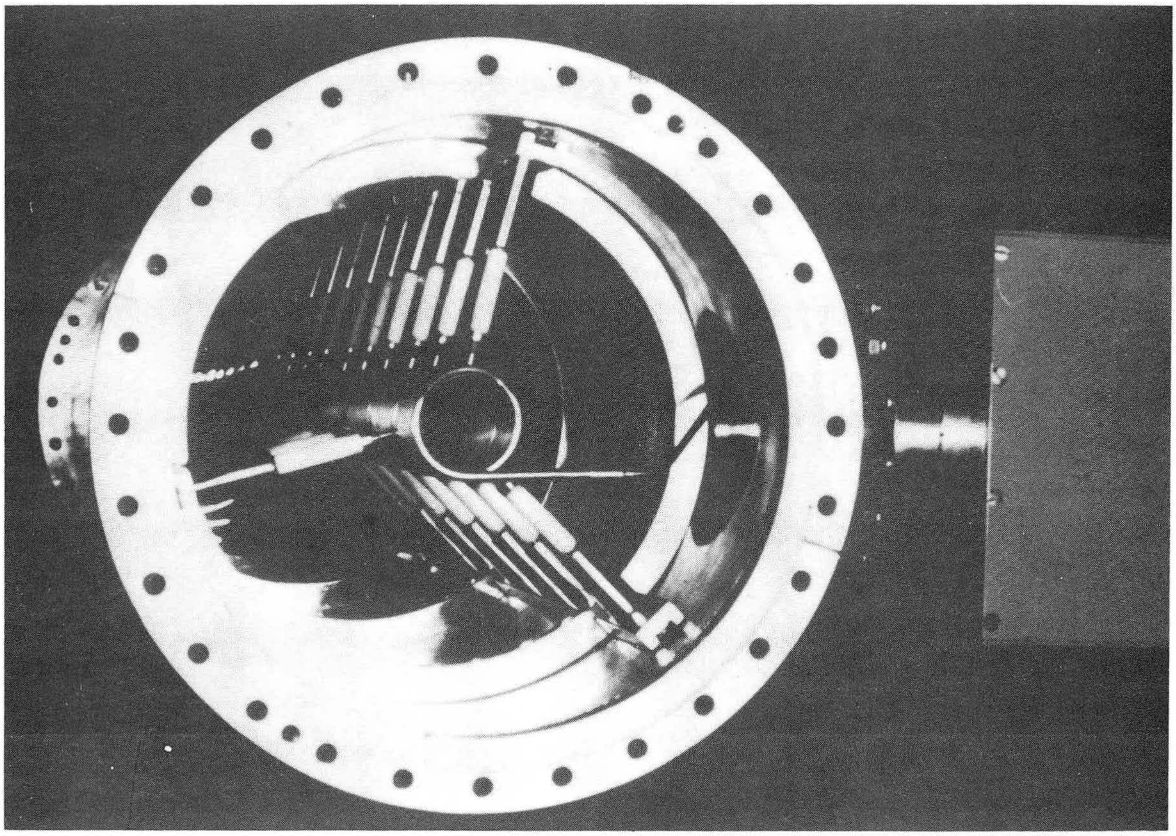

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Fig. 1a. Helical accelerator prototype.

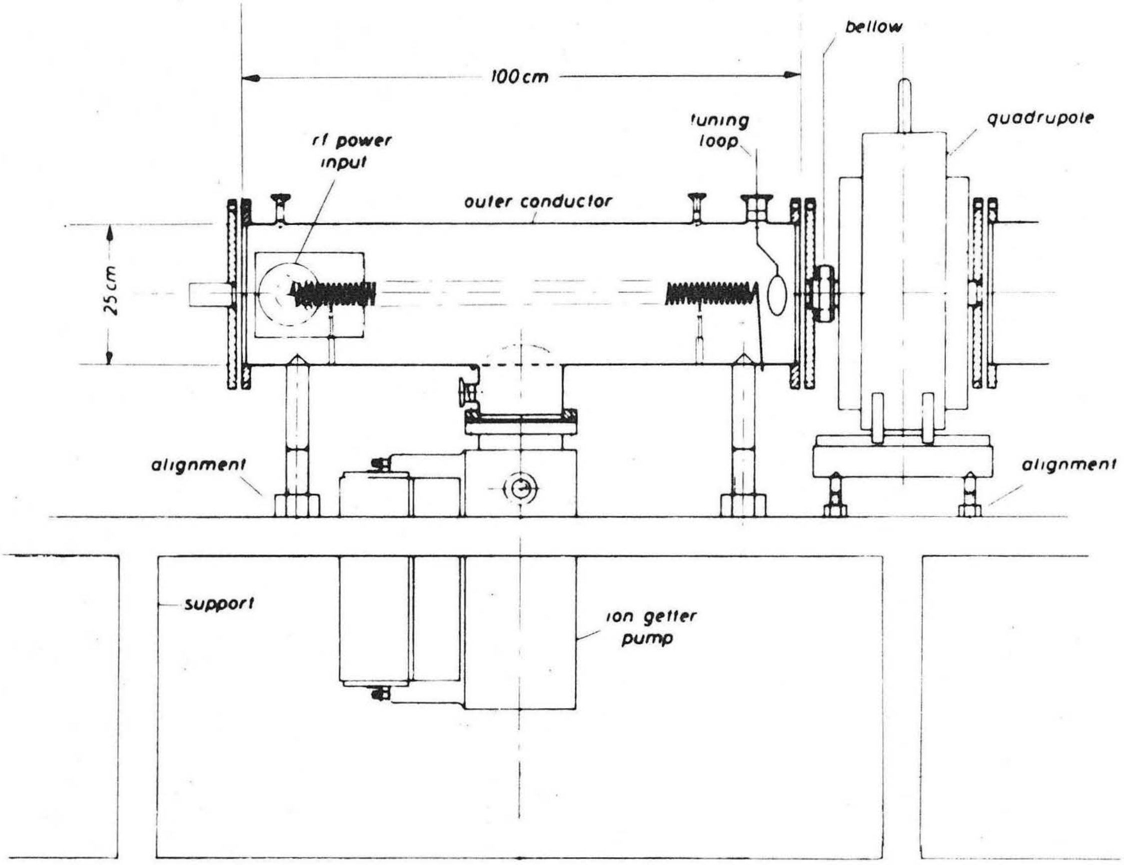

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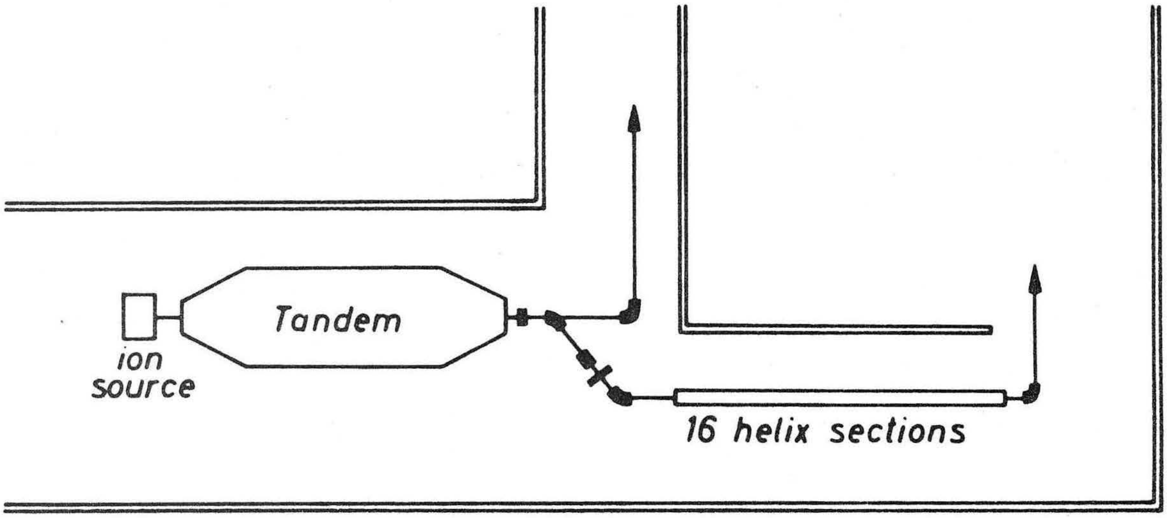
Fig. 2. Helac section - schematic.



Scheme of helix postaccelerator

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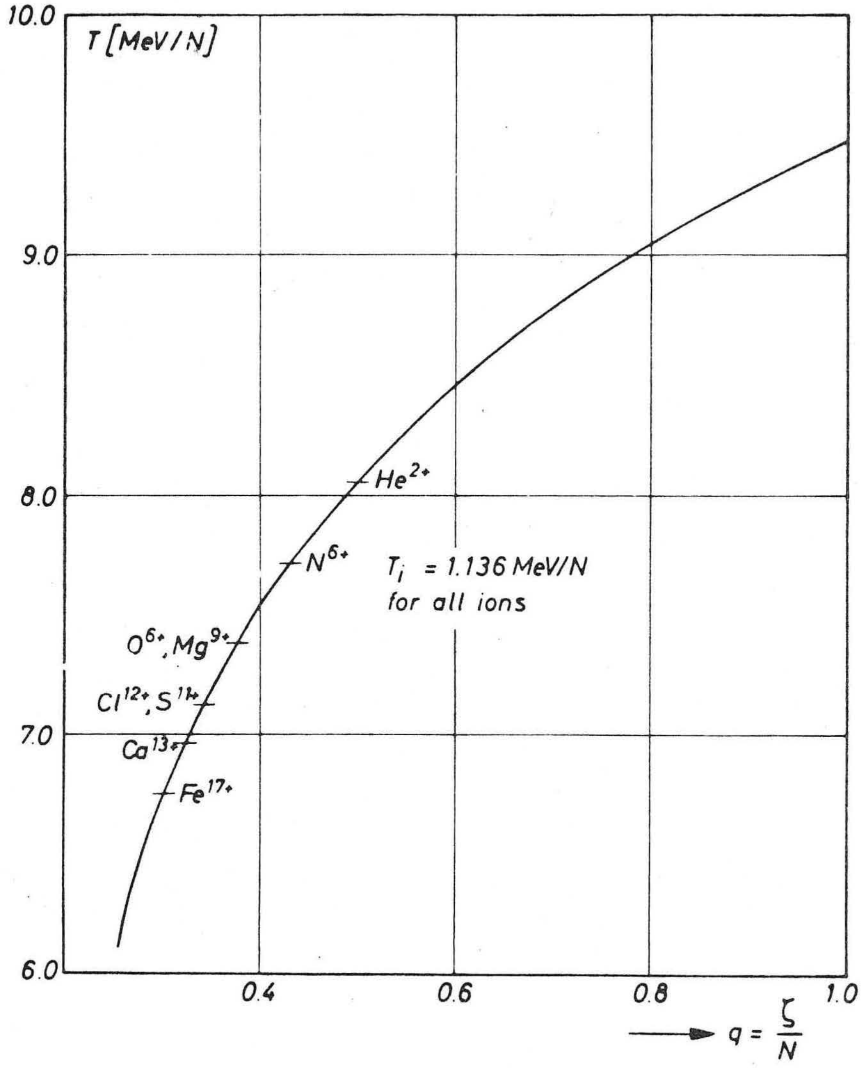
Fig. 3. Tandem Van de Graff - Helac plan.



Maximum energy versus specific ionisation
$q_{min} = 0.26$ ($T_i = 1.136$ MeV/N; $T_f = 6.122$ MeV/N)
16 sections

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Fig. 4. Maximum energy for various ions - Helac.

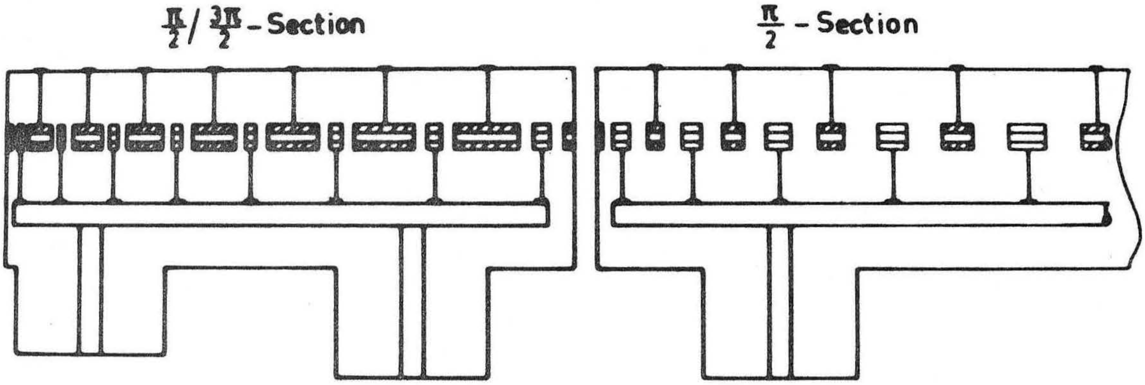

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Fig. 5. Unilac coaxial Wideröe scheme. Shaded drift tubes contain magnetic quads.

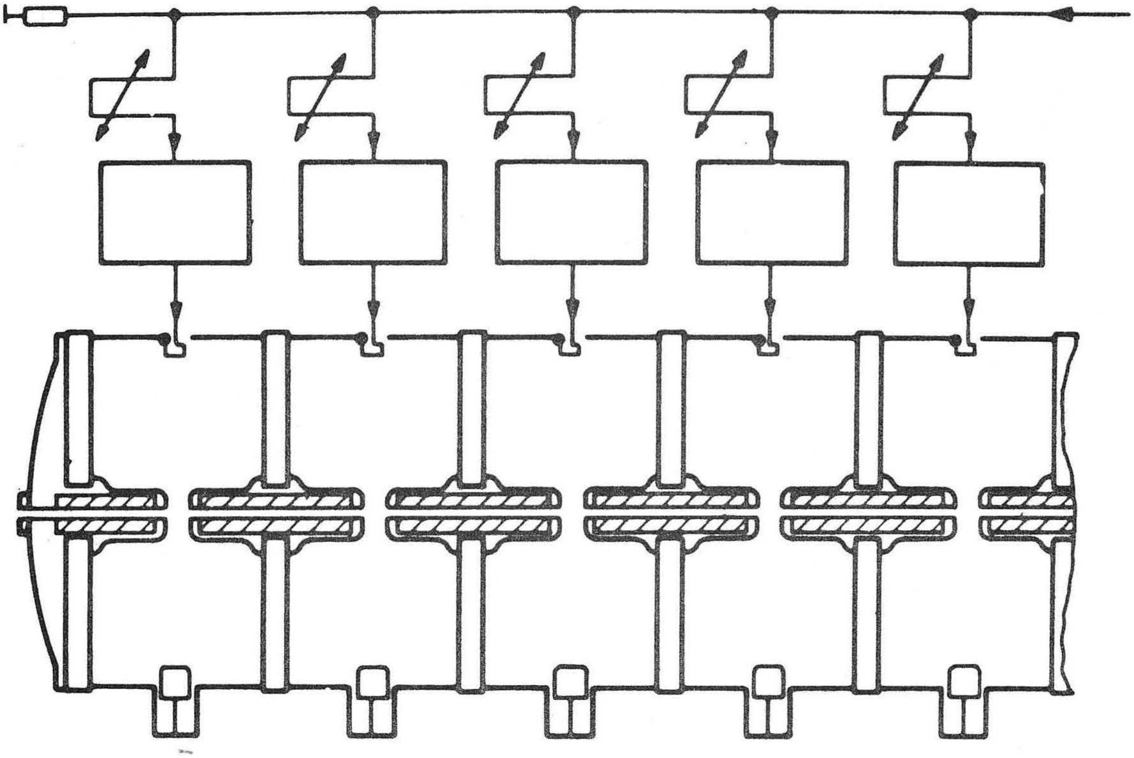

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Fig. 6. Unilac - single gap cavities - schematic.

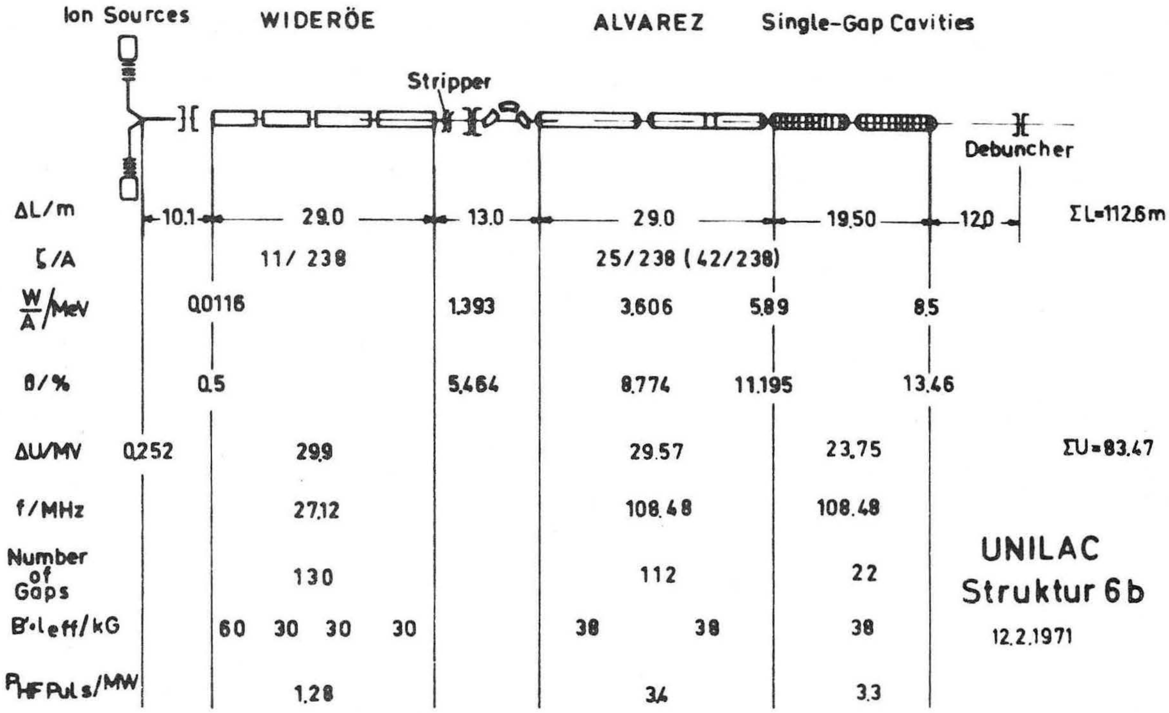

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Fig. 9. SuperHilac - drift tube - quadrupole design.

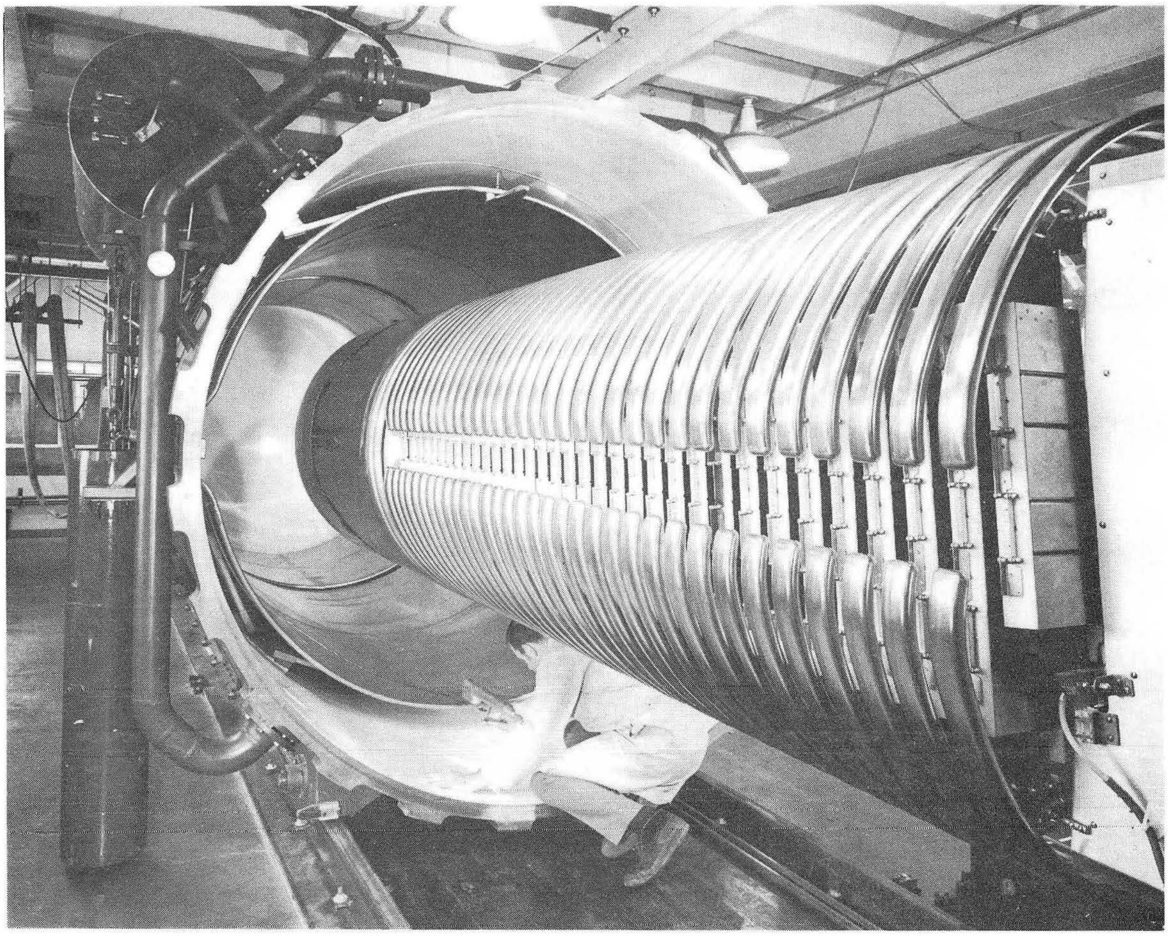

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Fig. 8. SuperHilac - 3 MV shunt-fed Cockcroft-Walton injector.

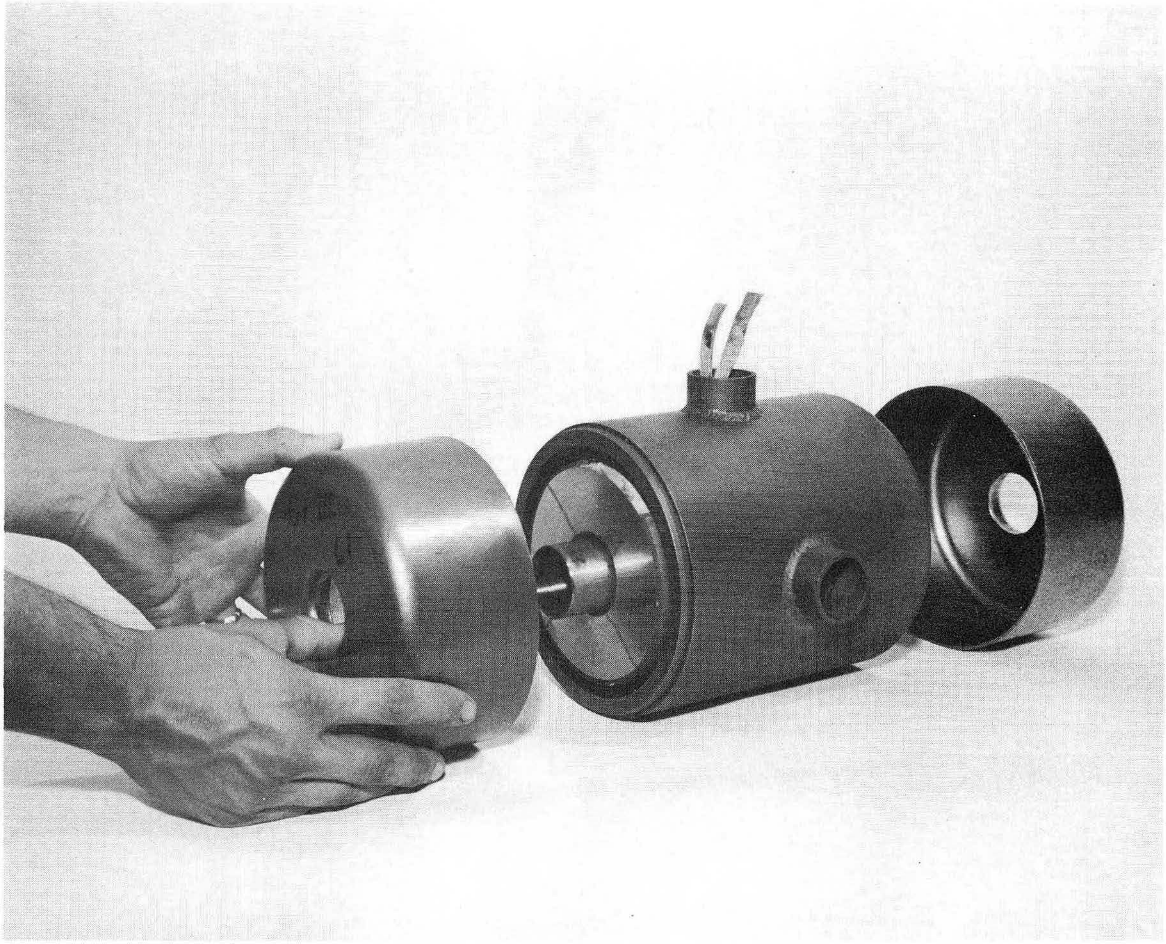

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Fig. 9. SuperHilac - drift tube - quadrupole design.

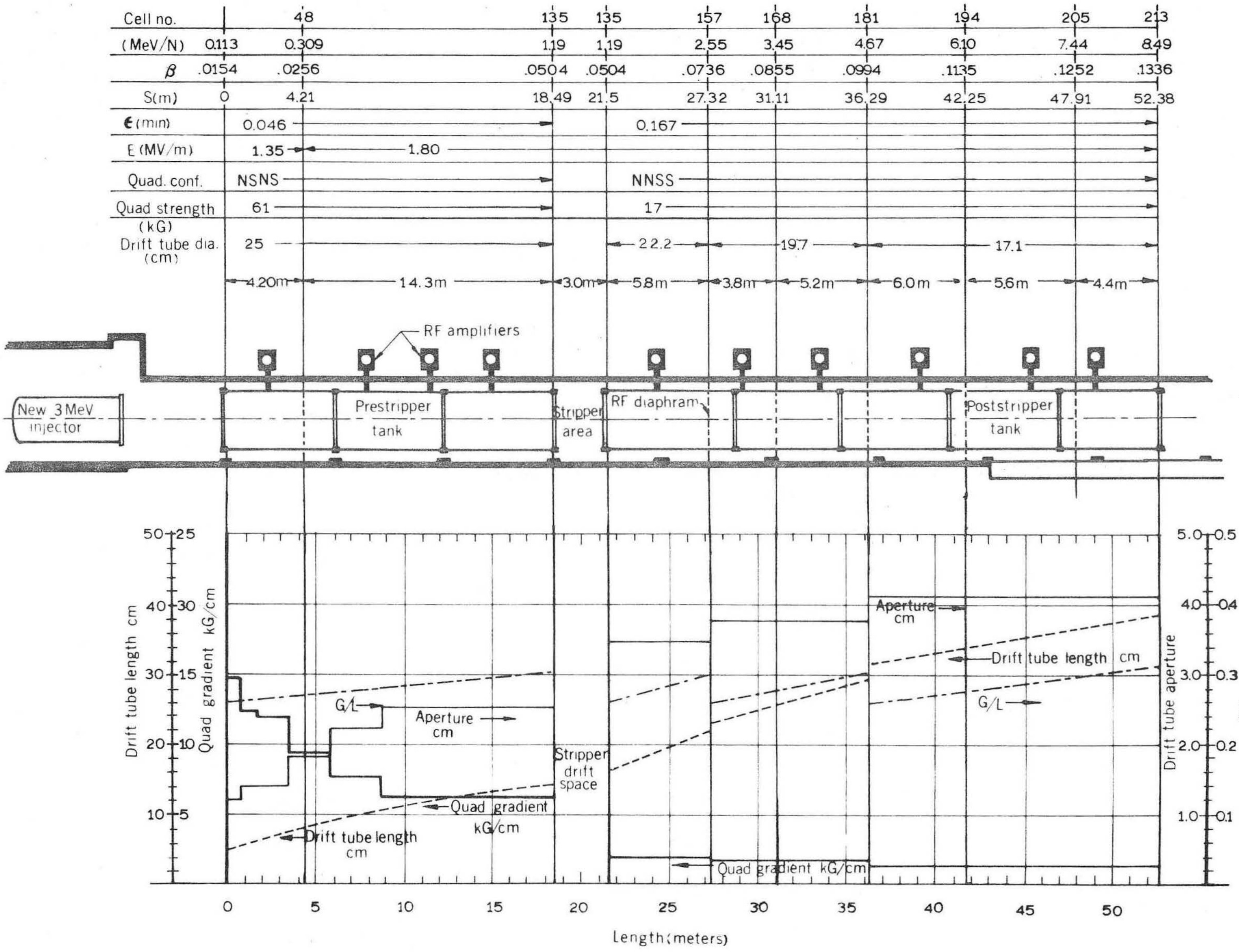

Fig. 10. SuperHilac - system layout and parameters.

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