HISTORY OF RFQ DEVELOPMENT

I.M.Kapchinskiy

The Institute for Theoretical and Experimental Physics, 117259, Moscow, USSR

Invited Paper

This report does not pretend to analyze the up-to-date situation with RFQ-focusing in proton, deuteron and heavy ion linacs. The main goal of the report is to make a short review of an appearance and preliminary development of the ideas pertaining to this method of particles focusing in linacs.

Several introductory remarks. In 1952 simultaneously with the strong fucusing principle invention, beam focusing in ion linacs by means of quadrupole magnets, placed within drift tubes, was proposed.[1] Static quadrupole focusing with the aid of magnetic lenses opened perspectives for a considerable increase of beam intensity and is used in the vast majority of ion linacs now operational in the world.

In modern proton linacs operating on the frequencies 150-200 MHz normalized acceptance of 1-1.5 cm.mrad is reached. The beam current limit, defined by the transverse repulsion, may be evaluated by the following ratio, which is correct when beam emittance is considerably less than the linac acceptance:

$$J_{max} = \frac{1}{2} j_0 B V_k , \qquad (1)$$

where B is the beam bunching factor, j_0 - parameter, having phase density dimension, in smooth approximation equal to

$$j_0 = \frac{A \mu J_0}{Z n \lambda} \beta ; \qquad (2)$$

where $I_0 = 4 \pi \varepsilon_0 m_0 c^3/e$ is the characteristic beam current for protons; Z,A are the charge state and atomic mass number of accelerated ions; n - focusing field period ratio to $\beta\lambda$; μ - transversal phase advance along the focusing period for the particles in the beam with negligible space charge density. For the alternating focusing in a smooth approximation it may be written:

$$\cos\mu = \cos\mu_0 - \gamma_c \sin\varphi , \qquad (3)$$

where μ_0 is transverse phase advance determined by focusing forces, γ_0 is RF defocusing factor

$$\gamma_c = \frac{Z \pi e U T}{2 A W_s} \cdot \frac{n^2}{2K} . \qquad (4)$$

U - amplitude of a potential difference over the acceleration period, K - the acceleration period multiplicity, W_s - synchronous particle energy, T - transit time factor, ϕ - the phase for a particle at the center of the gap. The beam bunching factor for the RF linac $B \sim 1/5$. Expressions (1-4) make it possible to evaluate the beam current limit. In proton linacs with magnetic quadrupole focusing beam current is limited to a value of 300 mA, when injection energy is not less than 700 keV.

The search for new methods of particle focusing in ion linacs continued, because electromagnetic quadrupole system (with all its merits, having made it practically speaking the only focusing method during the last 25 years) is not free from well known technological difficulties and it needs a very high injection energy.

Principally new methods, based on utilization the transverse components of RF acceleration field for focusing first started to appear in 1956. V.V. Vladimirskiy first proposed the idea of RFQ focusing[2]. Ja.B.Fainberg had formulated the suggestion of alternating phase focusing[3]. In this report we will follow only ideas pertaining to RFQ focusing.

Vladimirskiy's idea was to reject an axial symmetry of electric field in accelerating gaps. Drift tubes with fingers inserted into the accelerating gap were proposed. The azimuthal orientation of the fingers periodically changed by 90° (Fig. 1). Thus a sequence of RF quadrupoles with alternating polarity was created. The structure possessed spatial periodicity.

Independently from V.V. Vladimirskiy, V.A. Teplyakov with colleagues in 1962 proposed to implement a spatially-periodic RFQ-focusing by means of a system with drift tubes having rectangular aperture holes[4]. The orientation of the rectangular aperture holes is periodically changed by 90° (Fig. 2). The drift tubes with rectangular holes were also considered by the group of P.M. Lapostolle[5].

The equations of motion for the particles in a spacially-periodic RFQ focusing structure are:

$$\left.\begin{aligned} \frac{d^2x}{dz^2} &= \frac{Ze}{A\varepsilon_0\beta^2} \frac{\partial E_x}{\partial x}(z)\cos(kz+\varphi)\cdot x \\ \frac{d^2y}{dz^2} &= \frac{Ze}{A\varepsilon_0\beta^2} \frac{\partial E_y}{\partial y}(z)\cos(kz+\varphi)\cdot y \end{aligned}\right\} \qquad (5)$$

where $K = 2\pi/\beta\lambda$, ε_0 - the proton rest mass. Because $\frac{\partial E_x}{\partial x} + \frac{\partial E_y}{\partial y} = - \frac{\partial E_z}{\partial z}$, gradients of transverse components of the electric field in the accelerating gaps may be written in general as

$$\left.\begin{aligned} \frac{\partial E_x}{\partial x} &= -\frac{1}{2}\frac{\partial E_z}{\partial z}(z) + G(z) \\ \frac{\partial E_y}{\partial y} &= -\frac{1}{2}\frac{\partial E_z}{\partial z}(z) - G(z) \end{aligned}\right\} \qquad (6)$$

Then, with the relatively short (in comparison with focal distance) quadrupole gap spacings of the + - type structure the transverse phase advance in the first approximation is evaluated by:

$$\cos\mu_0 = 1 - \frac{1}{8}\left(\frac{SK^2}{l}\right)^2 \cos^2\varphi , \qquad (7)$$

where S - focusing period length, l - quadrupole gap spacings (Fig. 1), K - rigidity of the focusing channel.

It is convenient to write the expression for the rigidity of the focusing channel with quadrupole gaps in an universal form:

$$K^2 = \varkappa \frac{ZeU}{A\varepsilon_0}\left(\frac{\lambda}{2a}\right)^2 , \qquad (8)$$

where a is minimal half-width of a hole. For the channel with fingers the value of U coincides with the potential between adjacent fingers. The parameter characterizes efficiency of RFQ focusing, depending on the channel's structure. For the spatially-periodical channel

$$\varkappa = \left(\frac{2a}{\beta\lambda}\right)^2 F , \qquad (9)$$

where

$$F = \frac{l}{U}\int_L G(z)\cos kz\, dz . \qquad (10)$$

Integration is carried out over the acceleration period. As was shown by measurements in the electrolytic tank[5], F < 1, for the drift tubes with rectangular aperture holes, and focusing efficiency is, unfortunately, too low.

For the drift tubes with fingers in first approximation

$$F = \frac{\ell\beta\lambda}{\pi a^2}\sin\frac{\pi\ell}{\beta\lambda},$$

or

$$\varkappa = \frac{4}{\pi}\,\frac{\ell}{\beta\lambda}\sin\frac{\pi\ell}{\beta\lambda}, \qquad (11)$$

so that in the last case relatively high focusing efficiency might be reached. This assured perspectivity of fingered electrodes for the spatially-periodical RFQ focusing in ion linacs.

From equations (7-11) it follows, that focusing efficiency is higher, when the relative length of the gap of the acceleration period increases. But with long gaps the acceleration efficiency decreases significantly. The decisive step in the development of spatially-periodic RFQ focusing was made when in IHEP the structure was proposed with a double gap on every accelerating period[6]. One gap is restricted by fingers and determines in general the focusing effect, in the other gap an axially-symmetrical field with high acceleration efficiency is formed. The energy gain along the acceleration period increases correspondingly. With equal potentials on the gaps

$$\Delta W_s = \frac{1}{2} ZeU\left(T_1\cos\varphi_1 + T_2\cos\varphi_2\right), \qquad (12)$$

Phases ϕ_1, ϕ_2 at which the synchronous particle crosses the centers of focusing and accelerating gaps might be chosen so, that the parameters of radial and axial motion of particle will be optimized. Note that values cos μ_0 and γ_0 from (3) are connected with each other for RFQ focusing of any type. At the same time the focusing effect (1 - cos μ_0) is quadratic in relation to the RF field and the defocusing effect (γ_0) is linear. This imposes certain restrictions on the parameters of a linac with RFQ focusing.

The linac with periodic RFQ focusing was first constructed and launched in IHEP (Protvino) in 1972. Protons had been accelerated from 500 keV to 3.3 MeV with a particle capture coefficient of 25 %[7]. The frequency of the accelerating field was about 150 MHz, normalized acceptance - 1 cm.mrad. According to [1], the beam current capacity is not lower than in the Alvarez structure with the same injection energy. The authors refused to applicate cylindrical resonators on the E_{010} wave. The cavity proposed in IHEP with a longitudinal magnetic wave [8] makes it possible to relatively simply equalize the accelerating field along the longitudinal axis and it is more efficient than the cylindrical cavity loaded with drift tubes. By that, additional RF power consumption related to the transverse focusing field components have been compensated. A cross-section of the H-type cavity proposed in IHEP is shown in Fig. 3. As in a Wideröe cavity acceleration is realized on the π - mode wave.

A periodical structure developed in IHEP with RF quadrupoles favourably differs from the Alvarez structure by its technological simplicity, small transverse dimensions of the cavities and low cost.

The idea of spatially-homogenous quadrupole focusing (SHQF) has become a further step in the development of RFQ focusing. USSR patent on SHQF structure was received by V.V.Vladimirskiy (ITEP), I.M.Kapchinskiy (ITEP) and V.A.Teplyakov (IHEP) with priority from October 25, 1968[9]. First publications appeared in 1969[10,11].

The idea of SHQF was to substitute the structure with peridically spaced quadrupole gaps by the four-wire line which is homogeneous along the accelerator axis and possesses a quadrupole potential symmetry (Fig. 4). Because the homogeneous line is supplied with RF power, particles in the course of their motion along the axis will be successively affected by the fields with alternating gradient. It will lead to the appearance of a quadrupole focusing effect in a spatially-uniform system.

In a four-wire line a longitudinal accelerating field component can be introduced by a periodic change of the distance between the electrodes with a period of $\beta\lambda$. A schematic cross-section of modulated electrodes in the planes XOZ and YOZ is shown in Fig. 5. The electrode modulation phases in the planes XOZ and YOZ are shifted by modulation half-periods. Let m be electrodes modulation coefficient equal to the ratio of maximum and minimum distances from the axis, to the electrodes, U_L - the value of amplitude potential between adjacent electrodes. An effective accelerating potential on the acceleration period ($\beta\lambda/2$) is $U = HU_L$, where in the first approximation, that is, taking into account the major accelerating harmonic[12],

$$H = \frac{m^2 - 1}{m^2 I_0(ka) + I_0(mka)} \qquad (13)$$

If ϕ - the field phase when particle is in a plane with quadrupole cross-section, the energy gain over the acceleration period is

$$\Delta W = \frac{\pi}{4} ZeU\cos\varphi. \qquad (14)$$

The focusing effect in (3) is determined in a smooth approximation by term 12

$$\cos\mu_0 = 1 - \left(\frac{K^2}{\pi}\right)^2, \qquad (15)$$

where

$$K^2 = \varkappa\,\frac{ZeU_L}{A\mathcal{E}_c}\left(\frac{\lambda}{2a}\right)^2. \qquad (16)$$

Focusing efficiency decreases as the accelerating efficiency increases

$$\varkappa = 1 - H I_0(ka), \qquad (17)$$

but both parameters can be made high enough.

Spatially-uniform RFQ focusing has proved to be interesting first of all by the fact that the focusing rigidity is independent not only of the particle energy, but also of the particle phase in relation to the RF field. All particles within the transverse acceptance of the linac are focused approximately in the same way. The structure of the electrodes makes it possible to vary the acceleration efficiency H and synchronous phase ϕ_s in wide limits. The initial value of the synchronous phase might be taken as -90°. The procedures of H and ϕ_s along the axis of the accelerator have been proposed, which lead to practically complete bunching of the beam [13,14], later these procedures have been generalized in LANL[15]. The capture of the particles into resonant acceleration may reach 95-97 %. The modulation period of the electrodes might be small enough to let the injection energy be low. But with low input energies a high value of the beam current limit is kept, because the bunching coefficient at the accelerator input is close to one.

In a structure with spatially-homogeneous RFQ focusing the acceptance rotates with a frequency of the RF field. It created serious difficulties for matching the accelerator with the electrostatic injector. The invention in LANL of the beam matching method with help of an input horn has proved to be an important achievement[15]. It is shown that the horn makes it possible to match, at the accelerator input, the acceptances of different phases of the RF field. The matching of the low energy section (with spatially-homogeneous RFQ-focusing) to further sections of the accelerator (for example, to Alvarez cavities) should not be a problem, because at the output of the low-energy section the bunches' phase lengths are already relatively short.

The four-chamber resonator with longitudinal magnetic wave (Fig.6) was suggested for RF driving of the accelerating and focusing four-line structure in the patent formula in 1968. Figures 5 and 6 are borrowed from the patent description[9]. First evaluations of a four-line resonator are made in[10].

Practical realization of a spatially-homogeneous RFQ-focusing structure, as well as a structure with quadrupole gaps was done for the first time in the world in IHEP[16,20]. With that the idea of four-chamber resonator utilization was rejected in IHEP. It was found to be reasonable to drive the four-line structure by the so-called double H-resonator (Fig. 7)[17], because the latter provides a larger main frequency shift from the parasitic dipole modes frequency and simplifies the RF power supply of the resonator. Double H-resonator driving is conducted by one loop inserted in its outer volume[18]. Lathed cylindrical electrodes with alternating radius and conic transitions were used for technological reasons. A 150 MHz injector for the proton synchrotron's booster was constructed in IHEP. Fig. 8 shows a view of the new IHEP injector[19].

The utilization of the RFQ-focusing makes the linear accelerators-injectors simpler and cheaper. But this task is not so imperative, because the price share of the accelerating-focusing structure is only 15-20 % of the overall price of the accelerator. Simplification or removal of the focusing element's power supply also are not of principal importance, though they are useful. In ITEP, IHEP and other centers perspectives of RFQ focusing applications in linacs have been formulated as: design and construction of high intensity neutron generators for material irradiation testing, connected to HIF problems; obtaining of the high proton currents for electronuclear breeding of nuclear fuel; small-scale accelerator construction for industrial, technological and medical purposes. The need for heavy ion linac design and development for nuclear physics experimental installations and superheavy low-charged ion linacs for ICF has also arisen.

After a certain interruption, ITEP returned in 1976 to the development of the spatially-homogeneous RFQ focusing structure in connection with the project study of a high current linac for irradiation material testing[21]. In 1977 similar work started in LANL[22]. Both scientific centers independently returned to four-chamber resonators. Major considerations of ITEP scientists related to the possibility of a drastic simplification of the resonator cooling problems and to simpler measurements of the azimuthal field distribution. Some results of works carried out in ITEP are shown in [23,24,25]. The work in ITEP started with investigation of a four-chamber resonator driven on low level power. Measurements showed that in a four-chamber resonator each quadrupole mode is followed by two dipole modes with their frequencies several percent higher than the quadrupole mode frequency. To suppress parasitic dipole modes there have been vane strappings between opposite electrodes proposed and investigated. Photo (Fig. 9)[23] shows one of the "cold" four-chamber resonator models. The strapping can be seen on the photo. The second galvanic strap was installed on the other end of the resonator. To suppress parasitic dipole modes in a four-chamber resonator for the first time RF-feeding of all four chamber has been used with four properly phased driving loops. The study of different methods of azimuthal field levelling and levelling of the field along the longitudinal resonator axis led to a decision to install 32 moving plates, four plates in each of the eight resonator sections. To form the electrical field in the near-axis region electrodes of fixed curvature have been proposed making it possible to decrease the surface field at a chosen voltage between adjacent electrodes. Fig. 10 schematically shows the IHEP cylindrical electrodes (a)[20] and ITEP electrodes of permanent curvature (b)[25]. Photo (Fig. 11) shows the 3 MeV proton accelerator with SHQF constructed in ITEP. The resonator excitation frequency is 150 MHz, the injection energy is 90 keV. The capture coefficient for particles within the transverse acceptance is about 97 %. The beam current in 1982 was 100 mA[25].

The works conducted in LANL under general supervisions of Dr. E.A.Knapp and Dr. R.A.Jameson were important for the development of SHQF structures. In LANL the matching input horn has been proposed, the manifold, which provided even distribution of RF power for all four chambers with only one driving output from RF generator; new end elements for resonator tuning have been developed. The LANL constructional and technological developments have been of great importance. In 1980 there was successfully launched a prototype accelerator with SHQF[14] at a frequency of 425 MHz. It has achieved a 26 mA proton beam at an energy of 640 keV with a particle capture coefficient of 87 % [26]. This result is a fine achievement taking into account the small dimensions of the prototype. (Fig. 12)

LANL research and numerous publications in English have played the decisive role in the spreading of the interest to SHQF structures. At present in not less than 15 scientific centers of USSR, USA, FRG, Japan, France and Canada research of linacs based on the SHQF structure is being carried out.

With that it is possible to finish a short review of the appearance and preliminary development of ideas of RFQ-focusing in ion linacs.Modern state of the art in this field is reviewed completely enough in an excellent review of Prof.H.Klein[27]; the report has abundant references.

Today it has become clear that SHQF structures can be utilized in linacs for different trends of energetics development , in particular for installations of electronuclear breeding[28] and heavy ion ICF[29].For the acceleration of low charged heavy ion of high intensity SHQF structures with lumped resonant elements[27] are developed. In a number of scientific centers it is planned to use SHQF linacs as a low-energy section for synchrotron injectors.

References

1. J.P.Blewett, Phys.Rev., 1952, Vol.88, p.1197
2. V.V.Vladimirskiy, Prib. i Techn.Exper., 1956, No.3, p.35
3. Ja.B.Fainberg, CERN Symposium on High Energy Accelerators and Pion Physics, Genève, 1956, Vol.1, p.91
4. G.M.Anisimov, V.A.Teplyakov, Prib. i Techn.Exper., 1963, No.1, p.21
5. F.Fer et al., Proc.Int.Conf. on High Energy Accelerators, Dubna, 1963, Gosatomizdat, Moscow, 1964, p.513
6. A.P.Maltzev et al., Atomnaya energiya, 1967, Vol.23, p.195
7. S.A.Il'evskiy et al., Preprint IHEP, INJ 72-17, Serpukhov, 1972
8. V.A.Teplyakov, V.B.Stepanov, Radiotechnika i Electronika, 1968, Vol.13, p.1965
9. V.V.Vladimirskiy, I.M.Kapchinskiy, V.A.Teplyakov, Bulletin of Inventions, 1970, No.10, p.75, Patent USSR No.265312
10. I.M.Kapchinskiy, V.A.Teplyakov, Preprint ITEP No.673, Moscow, 1969
11. I.M.Kapchinskiy et al., Proc. VII Int. Conf. on High Energy Accelerators, Erevan - Zahkadsor, 1969, Publishing House Acad. Armenian SSR, 1970, Part 1, p.153
12. I.M.Kapchinskiy, Preprints IHEP INJ 72-29, INJ 72-30, Serpukhov, 1972
13. I.M.Kapchinskiy, V.A.Teplyakov, Preprint IHEP INS 69-48, Serpukhov, 1969; Prib. i Techn.Exper., 1970, No.4, p.17
14. A.P.Maltsev et al., Preprint IHEP 71-116, Serpukhov, 1971
15. K.R.Crandall et al., Proc. 1979 Linear Accelerator Conf., Montauk, USA, p.205
16. N.I.Golosai et al., Atomnaya Energiya, 1975, Vol.39, p.123
17. V.A.Teplyakov, V.B.Stepanov, Bulletin of Inventions, 1971, No.13, p.226, Patent USSR No.300970
18. A.A.Egorov et al., Preprint IHEP, OI 79-105, Serpukhov, 1979
19. Ju.M.Ado et al., Proc. VII All-Union Conf. on Particle Accelerators, Serpukhov, Oct. 1979, Dubna 1981, Part 2, p.354
20. B.M.Gorshkov et al., Journal Techn. Phys., 1977, Vol.47, No.11, p.2328
21. I.M.Kapchinskiy, Prib. i Techn.Exper. 1977, No.4, p.23
22. J.M.Potter et al., IEEE Trans. on Nuclear Sci., June 1979, Vol. NS-26, No.3, p.3745
23. M.L.Gusev et al., Preprint ITEP-49, Moscow, 1980
24. R.M.Vengrov et al., Proc. 1981 Linear Accelerator Conf., Santa Fe, USA, LA-9234-C, p.92
25. I.M.Kapchinskiy et al., IEEE Trans. on Nuclear Sci., August 1983, Vol. NS-30, No.4, p.3579
26. J.E.Stoval et al., IEEE Trans. on Nuclear Sci., April 1981, Vol. NS-28, No.2, p.1508
27. H.Klein, IEEE Trans. on Nuclear Sci., August 1983, Vol. NS-30, No.4, p.3313
28. P.Grand, ibid., p.3057
29. R.Bock, ibid., p.3049

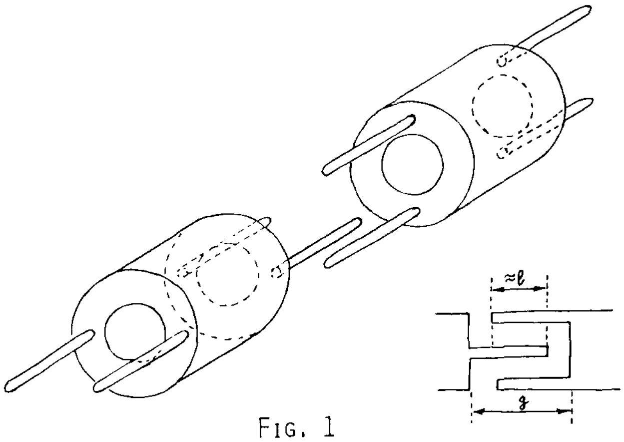

FIG. 1

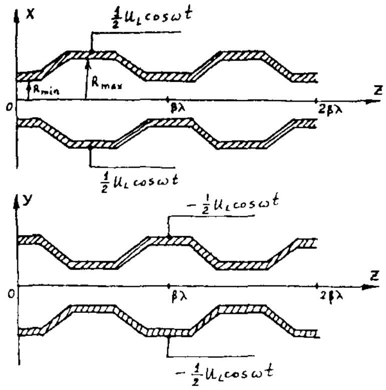

FIG. 5

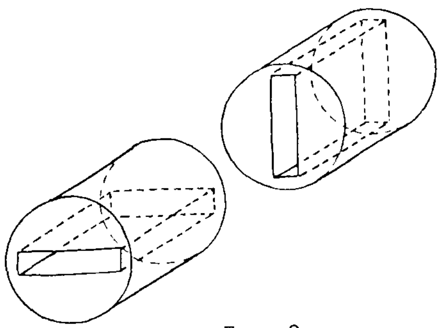

FIG. 2

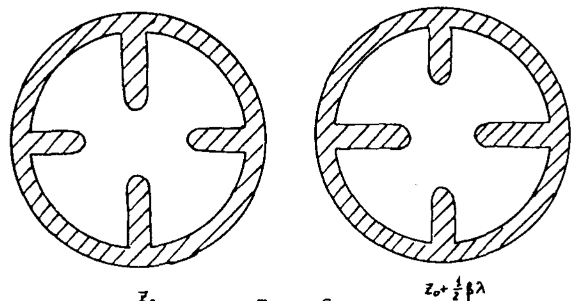

FIG. 6

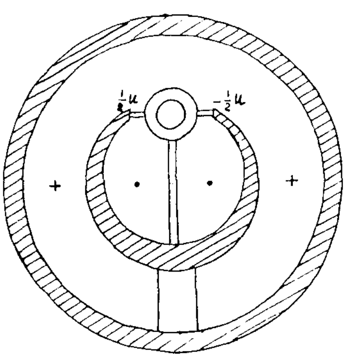

FIG. 3

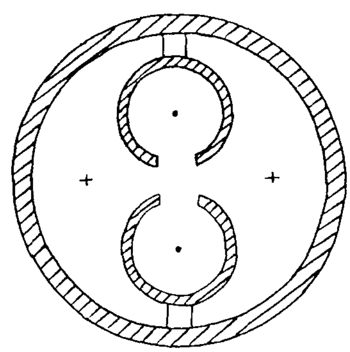

FIG. 7

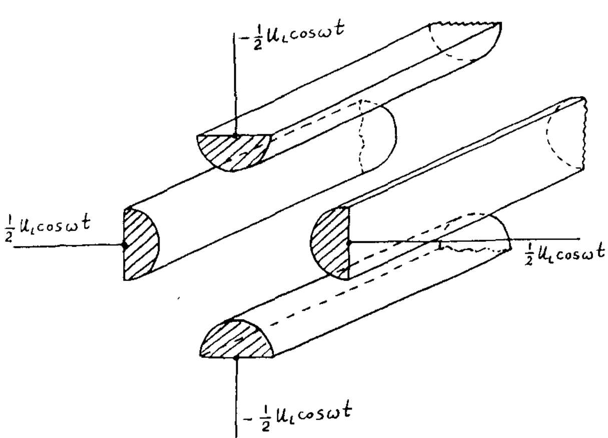

FIG. 4

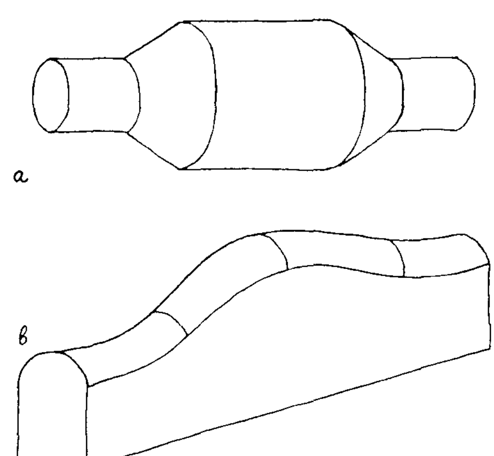

FIG. 10

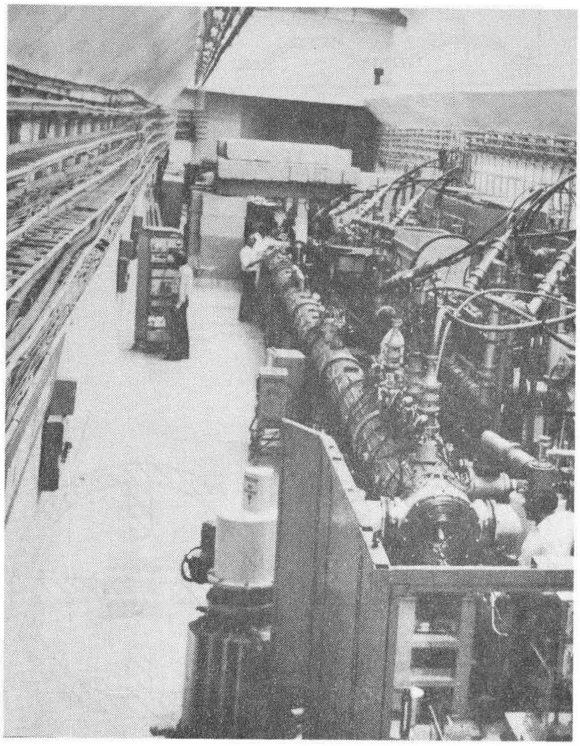

FIG. 8

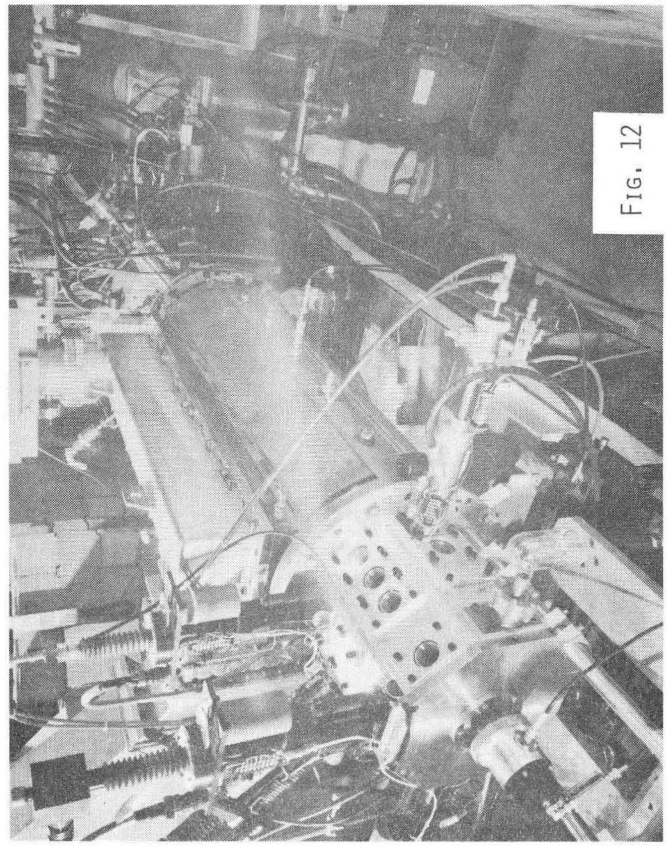

FIG. 12

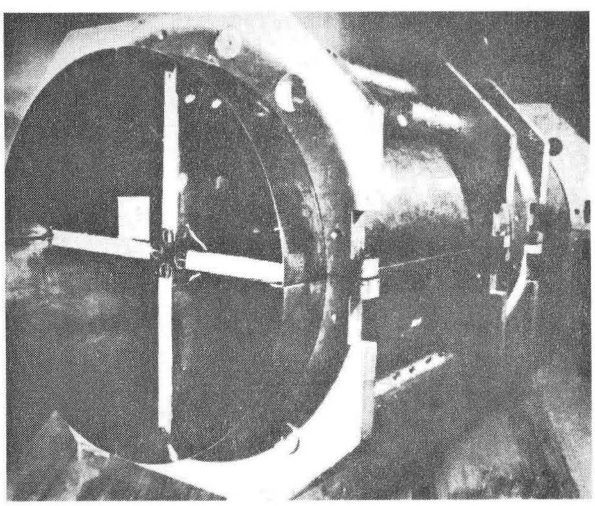

FIG. 9

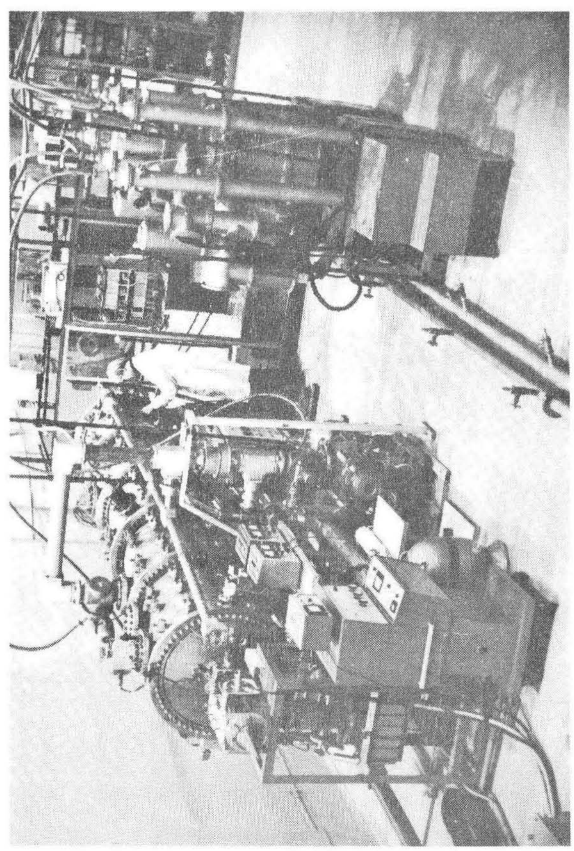

FIG. 11