Study of a Variable Energy Heavy Ion Linear Accelerator

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Abstract

After a review of problems typical for heavy ion acceleration, plans for a variable energy heavy ion linear accelerator are discussed. Energy variation is obtained in the last section of the accelerator by adjustable excitation of the individual, equidistant gaps. For uranium ions the accelerator will cover a range from 2 to 9 MeV/AMU.

Introduction

Interest in the heavy ion accelerator discussed in this note arose almost ten years ago in connection with speculations about the stability of double magic nuclei in the mass region around 300 AMU, stimulated by the work of Wheeler on superheavy nuclei (ref.1). An accelerator capable of producing beams of atomic ions up to uranium, with sufficient intensity (about 10^{12} particles per second), good phase space quality and continuously variable energy within the specific energy range from 2 to 9 MeV/AMU*) would, however, not only open a wide field for nuclear structure work and nuclear chemistry. Also in atomic and solid state physics, radiation chemistry and radiobiology many new experimental possibilities are envisaged. Such an accelerator should therefore provide a useful research tool for a considerable period of time.

The present study of such a <u>UNI</u>versal <u>L</u>inear <u>AC</u>celerator was carried out in Heidelberg during the last four years. Two main lines had to be followed, namely

(1) the study of accelerating structures, capable of handling the initially very slow ions ($\beta = 0.005$ at injection) on one side, as well as of producing beams of continuously variable energy on the other, and

(2) the collection of more information about the variation of ionic charge due to collissions with matter,

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*) The lower energy limit overlaps with the maximum energy for uranium ions obtainable with sufficient intensity from modern electrostatic machines, whereas the upper limit lies sufficiently above the Coulomb barrier for collissions with uranium nuclei at rest.

especially for very heavy atoms. The phenomenon of charge variablility does not only influence accelerator design, but experiments with charged heavy particle beams as well

Variation of ionic charge

The average equilibrium charge

Ions colliding with matter generally capture or lose one or more electrons. After a sufficient number of collissions an equilibrium charge distribution is reached. The envelope of this distribution is roughly gaussian. At sufficiently high velocities ($\beta \gtrsim 0.015$) the half width Γ of the distribution is approximately constant and proportional to $Z^{1/2}$ (fig.1). The weighted average equilibrium charge number

$$\bar{\zeta} \equiv \sum_{\zeta} \zeta N_{\zeta} / \sum_{\zeta} N_{\zeta}$$

is velocity dependend and follows for $Z \gtrsim 7$ and $\beta \gtrsim 0.01$ the simple empirical exponential relation

$$\bar{\zeta}/Z = 1 - C \exp\{-\delta\beta/\alpha\} ,$$

where the constants C and δ depend on the type of ion and on stripper properties. α is the fine structure constant. (See fig.2 and ref.2,3) At given velocity, $\bar{\zeta}$ is larger for dense (foil-) than for dilute (gas-) strippers. This simple relation may be extrapolated up to almost 10 MeV/AMU for the lighter atoms ($A \lesssim 50$). This is no longer true for heavy atoms like iodine or uranium (ref.4). The bend in the semilogarithmic $\bar{\zeta}(\beta)$-plot of fig.2 for foil stripped iodine ions - it occurs at $\bar{\zeta} \cong 25$ - indicates, that here shell effects begin to play an important role in the stripping process: at $\bar{\zeta} = 25$ the o-and n-shells of iodine are removed. From then on $\bar{\zeta}$ grows more slowly with increasing β than before.

Charge variation cross sections

So far relatively little is known about the charge variation cross sections for heavy ions. Therefore an attempt was made (ref.5) to compute their velocity dependence at least for variations by ± 1 charge unit. The calculation is based upon measurements of equilibrium charge distributions (ref.6). Typical results for total charge variation cross sections are shown in fig.3. In spite of the crudeness of the model used, the calculated values agree fairly well with the experiment in case of sulfur (ref.7). However, recent measurements with iodine ions (ref.8) deviate from the calculated values within a factor of three.

The cross sections increase rather rapidly with decreasing velocity due to the predominance of capture processes, but tend towards a flat maximum around approximately $\beta = 0.015$ (100 keV/AMU) (ref.9).

Consequences for accelerator design

The possibility of increasing the ionic charge stepwise by locally concentrated stripping allows to economize considerably on accelerator length. On the other hand, collissions of ions with residual gas atoms lead to distributed stripping, connected with particle loss or at least, a deterioration of phase space quality.

Number and position of strippers. Let us consider a typical example: 11^+

uranium ions shall be accelerated to 1650 MeV. Fig.4 shows the necessary total accelerating voltage for 0, 1 and 2 strippers placed at optimum positions. (Inspection of fig.5 shows, that the stripper position, optimized for minimum accelerating voltage, is not critical.) For comparison, the dashed line indicates the limiting case of an infinite number of strippers, i.e. of continuous stripping. Obviously little is gained by using more than one stripper. Considerations of the

Intensity loss due to stripping

amplify this statement. The distribution of charges after stripping causes intensity losses between aproximately 50 per cent for nitrogen and 85 per cent for uranium ions, provided, that only the most abundant charge state is separated for further acceleration. For more than one stripper the intensity problem therefore becomes serious.

It is worthwhile to recall that the linear accelerator allows simultaneous acceleration of ions in several neighbouring charge states. The accelerator described below could, for instance, accelerate uranium ions within the charge range $26 \leq \xi \leq 32$ simultaneously. The intensity loss due to stripping reduces thereby below 30 per cent, but strong coherent phase oscillations of ions with the "wrong" charge considerably increase bunch length and momentum spread. Still, such poor phase space properties may be tolerated in certain, e.g. radiochemical experiments.

Pressure transparency. As pointed out above, distributed stripping must be avoided. The vacuum system of heavy ion machines demands therefore special attention. Counting each stripping event in the residual gas of the vacuum chamber as particle loss, the ratio of ejected to injected particles, i.e. the pressure transparency, depends exponentially on the total charge variation cross section, on the pressure and on the particle path length. For a pressure transparency of better than 95 per cent the pressure in the main part of the proposed accelerator must be 1×10^{-6}Torr. Only along the first 3 meters of the accelerating structure the large capture cross sections of the heaviest ions demand a pressure of 2×10^{-7} Torr.

Proposed accelerating structure

A schematic diagram of the proposed accelerator is shown in fig.6. Table 1 contains further information about some important parameters.

The maximum specific energy of particles of different mass is plotted in fig.7 with the corresponding maximum duty cycle as parameter. The full and dashed curves refer to gas and foil strippers, respectively. The latter allow somewhat higher energies, but their poor heat resistivity severely limits the beam intensity.

The normal lower energy limit corresponds to 1.8 MeV/AMU, though it could be decreased further, in principle, by synchronous deceleration in the last section of the machine.

Let us now discuss the different elements of the proposed accelerator:

Ion sources and preaccelerator. The Berkeley type Penning source will be used for the heaviest ions. An extrapolation of performance data for krypton and xenon (ref.10) leads us to expect current yields of about 50 μA of uranium 11^+ ions. Recently, promising results were also abtained with a duoplasmatron, which produced about 200 μA of krypton 3^+ ions. Krypton 2^+ was the most abundant charge component (ref.11).

The 300 kV DC preaccelerator will be conventional. The relatively low voltage has been chosen for reasons of easy access and of economy. The preaccelerator will be followed by a 27 MHz prebuncher.

27 MHz section. The velocity of the injected particles is only 0.005 c. This dictates the rather low initial acceleration frequency of 27 MHz. The accelerating structure operates either in the 3π - or in an alternating π, 3π -mode below, and in the π -mode above $\beta \cong 0.02$.

Electrostatic quadrupoles will be used throughout this section. With a 3 cm drift tube bore the maximum potential of the lens electrodes will be about ± 25 kV, and the radial acceptance for phase stable particles is approximately 200 mm·mrad. More details about the focusing system and results of model measurements are given elsewhere in these proceedings.

There are five periods of phase oscillation along the 20 m long structure. The damping of phase oscillations is sufficient to match the phase emittance of the 27 MHz section to the phase acceptance of the following 108 MHz sections even by allowing for 2 m of drift path in between.

The prestripper Alvarez section is conventional and delivers ions at $\beta = 0.06$ (1.8 MeV/AMU) into the

Stripper region. A gas stripper is forseen for normal operation. It will be of the transverse supersonic jet type. Presently a CO$_2$ jet is under construction. The stripper will be followed by a magnetic charge separator capable of isolating uranium 50^+ ions. The rather unconventional separator postion has been chosen in ordner to avoid unwanted radiation background in the experimental hall. At 1.8 MeV/AMU radiation and beam power are quite low. The price we have to pay for this advantage is a drift path of 8 m (assuming conventional magnets) and hence the necessity to insert a rebuncher. It is planned to bypass the separation system for multiple charge acceleration if necessary.

In the poststripper Alvarez section the two central drift tubes can be excited separately. They serve as rebuncher if, for specific energies between 1.8 and 4 MeV/AMU, the remaining section is switched off.

Single resonator structure. A chain of 20 identical 108 MHz resonators form the last accelerating section. Each resonator is fed by its own power amplifier. By proper adjustment of phase and amplitude in the individual gaps the accelerating field can be made to match each desired "velocity profile" and any total accelerating voltage between zero and 28 MV. Phasing of the resonators will be done at the input of the RF power amplifiers. Although a phasing accuracy of ± 0.5 degrees is being aimed at, numerical calculations have shown that random phase errors within a ± 5 degree rectangular distribution do not seriously influence the phase space quality of the bunches (ref.12).

Separate RF power amplifiers have been selcted because a commercial television tube, Type RS 1082, is available, which delivers 200 kW pulse power at

20 per cent duty cycle and 50 Hz repetition frequency. Phase shifts in the power amplifiers will be eliminated by a fast correcting system governed by a phase comparison between the resonator field and the input signal to the amplifier. This system will be supported by a slow acting resonator tuning device.

Fig.8 gives an impression of part of this single resonator chain. Two complete cells have been biult and are being tested at present.

Cost. The total cost of the accelerator including RF, power supplies, vacuum- and cooling system has been estimated to 21 Million DM (about 5 M$). The same amount of money will be necessary for the accelerator building, the experimental hall and a few moderate service facilities. It will take about 4 years to built the machine.

Acknowledgements.

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References.

1) F.G.Werner and J.A.Wheeler; Phys.Rev. 109, 126 (1958)

2) H.H.Heckman, E.L.Hubbard and W.G. Simon; Phys.Rev.129, 1240 (1963)

3) H.-D.Betz, G.Hortig, E.Leischner, Ch.Schmelzer, B.Stadler and J.Weihrauch; Phys.Letters 22, 643 (1966)

4) L.Grodzins, R.Kalish, D.Murnick, R.J.Van de Graaff, F.Chmara and P.H.Rose; Phys.Letters 24B, 282 (1967)

5) H.-D.Betz and Ch.Schmelzer; UNILAC-Bericht 1-67 (1967)

6) E.Leischner; UNILAC-Bericht 1-66 (1966)

7) H.-D.Betz; UNILAC-Bericht 5-66 (1966)

8) N.Angert and A.Möller; to be published

9) V.S.Nikolaev, I.S.Dmitriev, L.N. Fateeva and Ya.A.Teplova; Sov.Phys. JETP 13, 695 (1961)

10) A.Ghiorso; IEE Trans. NS-14, 5 (1967)

11) H.Krupp; UNILAC-Bericht 1-68 (1968)

12) K.Blasche; UNILAC-Bericht 3-67 (1967).

DISCUSSION

(C. Schmelzer)

WATERTON, AECL: I was not clear whether this electroplating is what I would call electroforming. That is the deposition of the copper on a substrate which you subsequently throw away.

SCHMELZER, HEIDELBERG: Oh, this is my mistake. It is electroforming.

Table 1. Accelerator parameters.

	Wideröe	Alvarez I	Alvarez II	Single Res. Section
Particle Velocity $\frac{v}{c}$	0.005	0.046	0.062	0.092 0.062-0.25
Charge to Mass Ratio ζ/A	0.046-0.5	0.046-05	0.115-1	0.115-1
Tolerance of ζ/A f. mult. Charge Acc.	—	—	+15 % −10 %	+15 % −10 %
Vacuum Pressure/Torr	$2 \cdot 10^{-7}$	10^{-6}	10^{-6}	10^{-6}
Acceleration Mode	3π π	2π	2π	not defined
max. Acc. Rate /$\frac{MV}{m}$	1−1.5	1.35	1.75	1.2
max. Gap Gradient/$\frac{MV}{m}$	6	8.5	9	19
tot. Number of Gaps	ca. 100	86	50	20
tot. Acc. Voltage/MV	21.4	17.3	18.7	≤ 28
Strong Focusing	el. static	magn.	magn.	magn.
Quadrp. Polarity Grouping	N=1 N=3	N=2	N=2	N=1
max. Quadrp. Gradient	24−18 kV/cm^2	7kG/cm	4−2 kG/cm	0.6 kG/cm
Frequency/Mc/s	27	108	108	108
Shuntimped. $ZT^2/\frac{M\Omega}{m}$	ca. 50	31	36.5	(15)
max. RF Pulse Power/MW	ca. 0.8	1.2	1.45	4
tot. Number of 0.2 MW RF Ampl.	4	6	8	20

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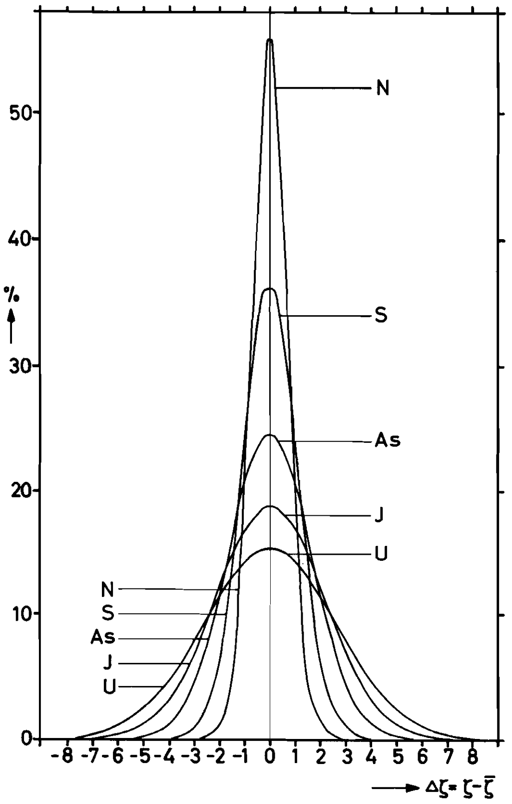

Fig. 1. Envelopes of normal equilibrium charge distributions after stripping above $\beta \simeq 0.015$.

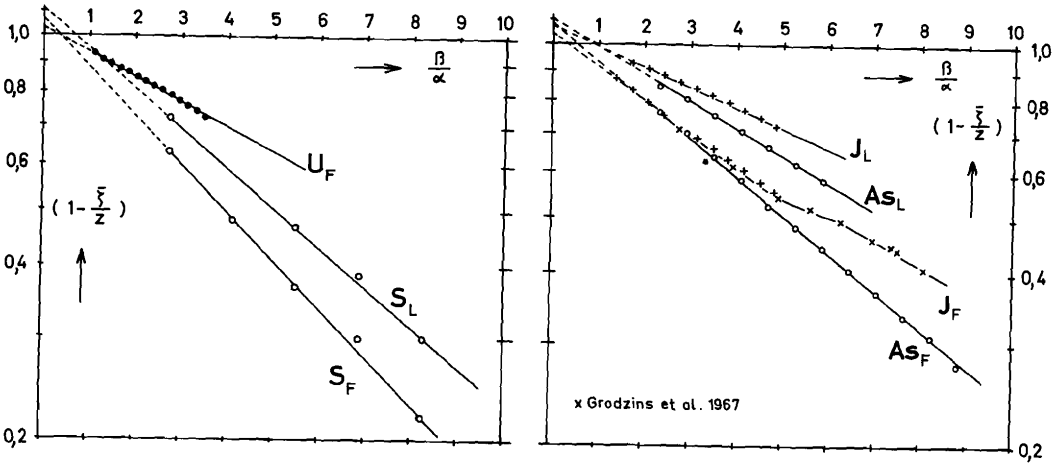

Fig.2. Relative equilibrium charge $\bar{\zeta}/Z$ vs. velocity.

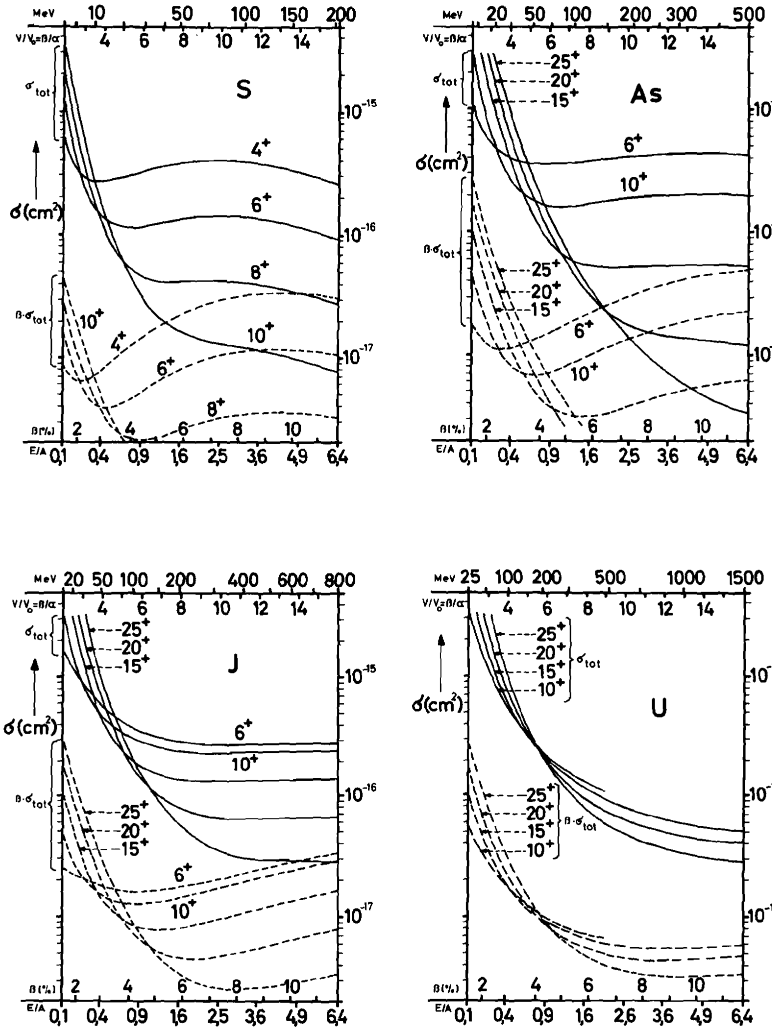

Fig.3. Calculated total charge variation cross sections.

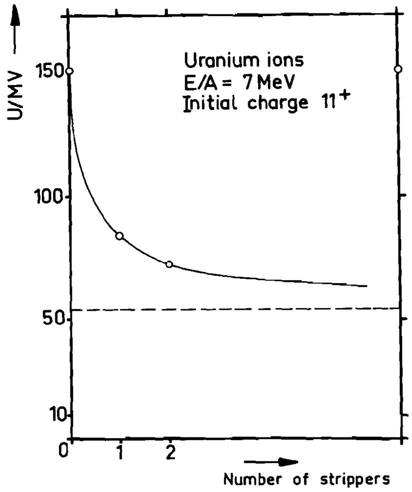

Fig.4. Total accelerating voltage vs. number of strippers.

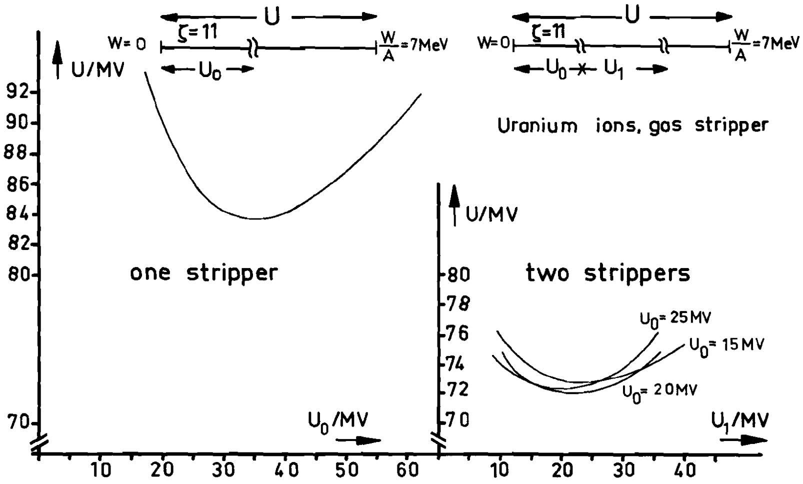

Fig.5. Total accelerating voltage vs. stripper position.

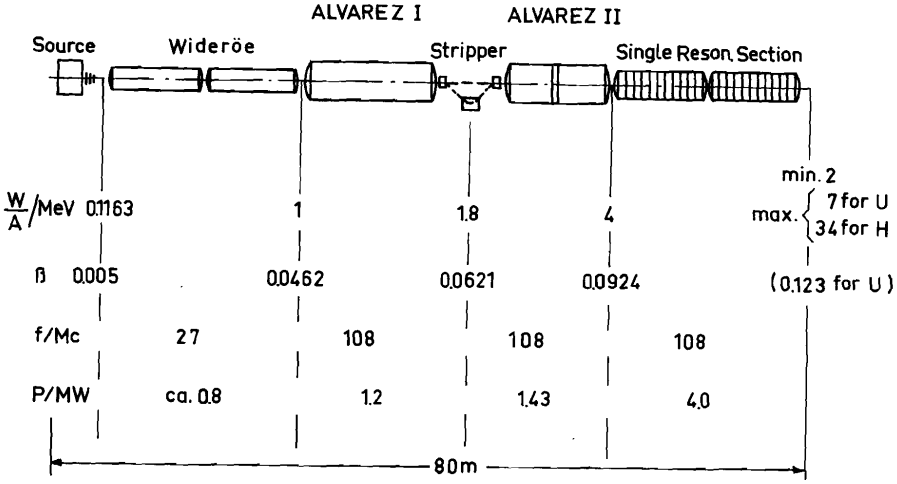

Fig.6. Schematic diagram of proposed accelerator.

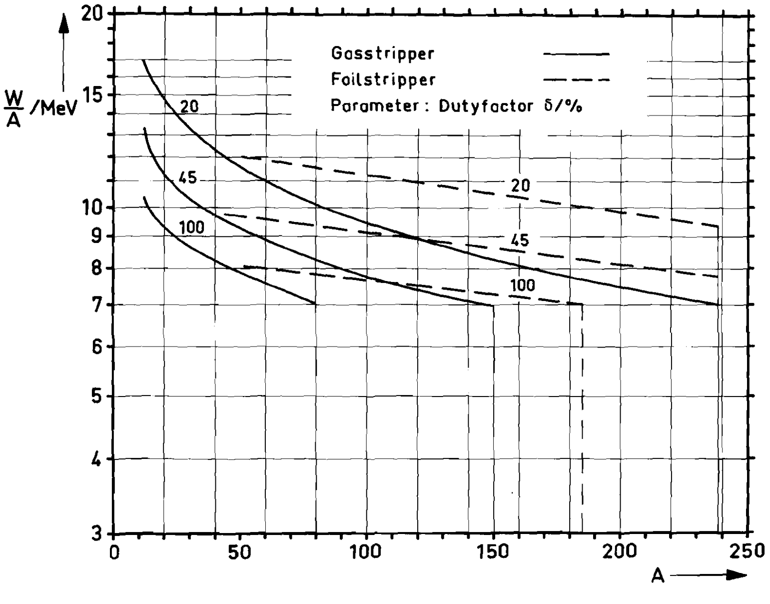

Fig.7. Maximum specific particle energy vs. ion species and duty factor.

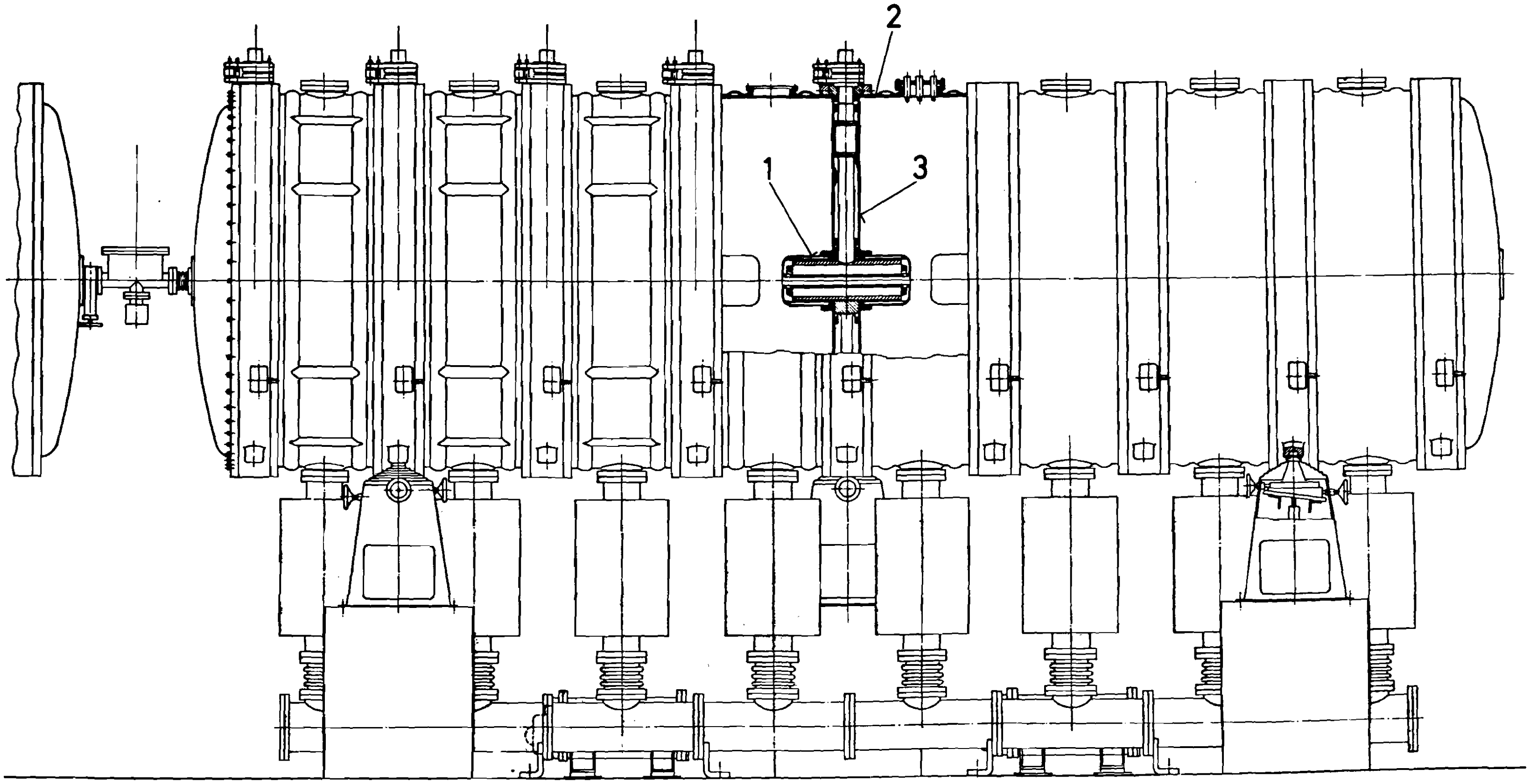

Fig.8. Elements of the single resonator section.