LINEAR ACCELERATORS EXCITED IN THE TE(111)-MODE*

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Summary

New applications for interdigital-H-structures have been proposed. Besides the normal operation as postaccelerators, IH-structures can be used for the acceleration of low energy molecular ions ($\beta \sim 1\%-2\%$), of ion beams ($3\% < \beta < 12\%$) between RFQ - or static injectors and Alvarez structures and of multiple low energy high current beams in a MEQALAC-system.

A theory has been developed, which allows the calculation of frequency and efficiency as a function of geometrical structure parameters within ±5%. Results for the various applications are presented.

IH-Accelerating Structure

An interdigital-H-type resonator consists of a cylindrical cavity, in which the drifttubes are alternately connected to opposite sides of the outer shell by either individual support stems (fig.1) or massive common bars. By this the existing transverse electric field of the undisturbed TE(111)-cavity-mode is bent in axial direction, leading to oppositely charged drifttubes ($\beta\lambda/2$-type accelerator) and a sinusoidal axial voltage distribution in the case of constant capacitive and inductive load.

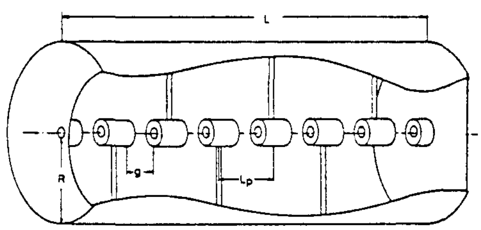

Fig.1 Schematic drawing of IH-structure

Investigations on this structure have been done in the Soviet Union[1], by groups in Lyon, France[2], and in Munich, Germany[3], where a 5MV postaccelerator for a 14MV MP tandem has been built. For extended postacceleration a smaller cavity operating with double frequency (2f-"Schwein") is under construction[4]. Two Japanese groups are working on IH-structures for the NUMATRON project[5] and a heavy ion postaccelerator for a 11MV pelletron tandem[6].

Calculation of Frequency

For the following considerations we will limit ourselves to set ups of IH-structures with identical $\beta\lambda/2$-cells and individual stems. In order to calculate the resonance frequency we start with a distributed equivalent circuit describing the dispersion characteristic of undisturbed TE(mn)-waves in cylindrical waveguides[7] (fig.2). ε and μ are the electric and magnetic field constants of the medium inside the waveguide. The cut-off wave number γ_{mn} for the TE(11)-mode is given by $\gamma_{11}=1.841/R$ with R representing the radius of the guide. The real drifttube structure is now taken into account by additional lumped circuit elements (fig.3). L_F relates to the inductance of one support stem, L_W to the inductance of the side walls and C to the total capacitance of stem and drifttube. L_r represents the axial inductance. A similar distributed equivalent circuit has been given by a Japanese group[5].

*Work supp. by BMFT; Calculations at HRZ

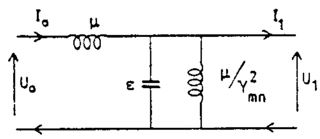

Fig.2 Distributed equivalent circuit for TE-modes in cylindrical waveguides

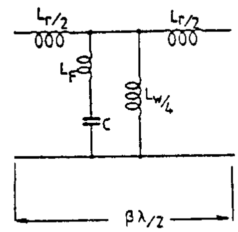

Fig.3 Lumped equivalent circuit for individual stem IH-structures

A structure with N identical cells is represented by a series connexion of N such circuits. The analysis of the system shows, that the frequency is determined by the phase shift μ per cell and is given by:

$$\omega^2 = \frac{1}{C} \cdot \frac{1 + \frac{L_W}{2L_r}(1 - \cos\mu)}{L_F \frac{L_W}{2L_r}(1 - \cos\mu) + \frac{L_W}{4} + L_F} \qquad (1)$$

Measurements of the current distribution showed, that the azimuthal current density on the side walls for one $\beta\lambda/2$-cell is nearly constant, whereas the current on the stem decreases from the point at the wall towards the drifttubes. In good agreement to the experiments the azimuthal current distribution can be calculated by the interpretation, that the support stems behave like a $\lambda/4$-line. Compared to the geometrical length l, the electrical length l* is lengthened by the capacitive (drifttubes) and inductive load (side walls). The inductance L_F and the stem capacitance C_F are given by the formulae of a loaded $\lambda/4$-line[11].

$$L_F = \frac{4}{\pi} \int_{l_1}^{l_1+l} L' \cos\left(\frac{\pi x}{2l^*}\right) dx \qquad (2)$$

$$C_F = \frac{\pi}{4} \int_{l_1}^{l_1+l} C' \sin\left(\frac{\pi x}{2l^*}\right) dx \qquad (3)$$

l_1 is the inductive lengthening.

To calculate the capacitive layer C' of the stems, the side walls, as well as the endplates of the structure are replaced by infinite series of image stems in axial and transverse directions. Since the axial voltage distribution is well known (sinusoidal) in the case of identical $\beta\lambda/2$-cells, the electric surface potential of one stem is given by summing up the potential parts of all real and image stems. For the numeric calculation the formula for the potential distribution outside a long homogeniously charged line is used[8], and the variing distances between the wall and the stem are taken into account. According to the approximate validity of the free space wave propagation, derived from experiments, we determine the inductive layer L' for a known value of C' from:

$$L' = \frac{1}{c^2 C'} \qquad (4)$$

Because of the limited space only the results for the other lumped elements in fig.3 will be given (for detailed explanation see ref.[9]). In accordance with the wall inductance for vacuum μ_0/γ_{11}^2 in fig.2 the wall inductance L_W is assumed as

$$L_W = \frac{\pi}{\beta\lambda} \; \frac{\mu}{\sin\mu} \cdot \frac{\mu_0}{\gamma_{11}^2} \qquad (5)$$

with μ representing the phase shift per cell. The axial inductance L_r is generated by the transverse electric field[10], therefore

$$L_r = \frac{1}{c^2 C_F} \left(\frac{\beta\lambda}{2}\right)^2. \qquad (6)$$

For the drifttube capacitance C_D a formula introduced by E. Müller[11] is used. The capacitive load C_L in terms of C_D is given as follows

$$C_L = 2C_D \cdot (1 + \cos\mu), \qquad (7)$$

the total capacitance C by

$$C = C_F + C_L, \qquad (8)$$

the inductive load L_L mainly by the wall inductance L_W.

The electrical length l^* of the stems in eqs. 2, 3 can be derived by numerical methods from the following expression for a loaded $\lambda/4$-line

$$\frac{\pi l C_L}{4 l^* C_0} - \cot\left(\frac{\pi l}{2 l^*} + \arctan \frac{4 l L_L}{\pi l^* L_0}\right) = 0. \qquad (9)$$

C_0 and L_0 relate to the lumped capacitance and inductance of the unloaded line; they can be obtained from eqs. 2, 3 with $l^* = l$ and $l_1 = 0$.

At first sight the equivalent circuit (fig.3) allows only next neighbour inductive coupling. But all lumped elements of the circuit are functions of the phase shift μ and therefore they have no constant value for different modes. This allows the consideration of capacitive and inductive coupling even between far distant cells.

Fig.4 shows typical dispersion curves for a model cavity together with the theoretical results. The correspondence turned out better than ±3%. The comparison between the theory and numerous measurements on individual stem IH-structures done by the Lyon group[2] also showed a good agreement (±5%).

Calculation of Efficiency and Q_0-Value

The efficiency of linear accelerating structures is given by the bare and effective shuntimpedance

$$\eta_0 = \frac{U^2}{P \cdot L}; \quad \eta_{eff} = \eta_0 \cdot TT^2 \qquad (10)$$

(U total resonator voltage, L cavity length, P RF power, TT transittime factor).

On the basis of the previous analysis on the equivalent circuit, the distribution of the power losses can be obtained. In contrast to efficiency calculations done by other authors[3] a consideration of all occuring losses, including those produced by the axial currents, is possible. Especially the non constant current distribution on the stem is taken into account. Since all calculations are carried out by numerical methods, no analytical formulae for efficiency and Q_0 can be given. Under certain conditions some approximations can be made. For long resonators (small phase shift μ per cell) the axial currents can be neglected, and for a high capacitive load the current distribution on the stem is nearly constant, leading to the well known approximate formulae for shuntimpedance[3] and unloaded Q_0-value:

$$\eta_0 = \frac{N^2}{L^2} \; \frac{8}{\pi^2} \; \frac{F^2}{2\alpha D(\pi+2)} \; \sqrt{2\sigma\mu_0{}^3\omega^3} \qquad (11)$$

$$Q_0 = \frac{\omega\mu_0 V\delta\sigma}{L\alpha D(\pi+2)} \qquad (12)$$

(F free resonator cross section, D cavity diameter, V free resonator volume, σ electric conductivity, δ skin depth, α correction factor for the power losses due to the larger current density on the stems).

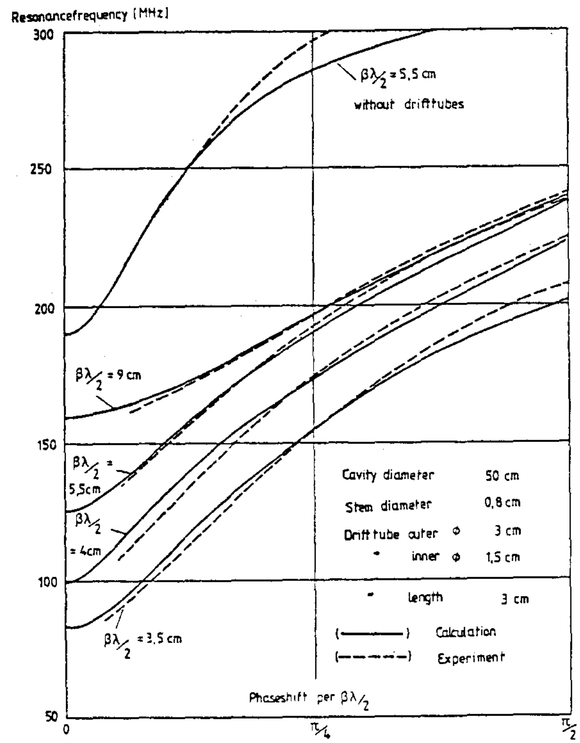

Fig.4 Dispersion characteristics

The theoretical calculations of frequency and efficiency allow the prediction of properties for individual stem IH-structures without previous measurements. On the basis of the complete theory, fig.5 shows possible realizations and shuntimpedances of IH-structures in a wide range of particle energies under the assumption of best copper conductivity. IH-structures are well suited for highly efficient acceleration, especially in the low beta region. Due to eq. 11 the shuntimpedance mainly depends on the particle velocity β (number of cells N per length for a given frequency) and the capacitive load. Thus resonators with high frequency for a given cavity diameter show the best efficiency.

Applications of IH-Structures

The effective shuntimpedance as a function of particle energy for selected individual IH-structures in comparison with experimental data of other linac cavities is summarized in fig.6. The data of the different IH-structures base upon fig.5 under the assumption of a reduced (-20%) conductivity.

Since postacceleration of ions and molecules can often be done without any quadrupole intank focusing, small radial dimensions of the drifttubes can be chosen. In this case, and for an energy range of 1-10MeV/u IH-structures show higher shuntimpedances (up to a factor of 4) and a more compact set up compared to Alvarez structures (curves 1, 2, 3 fig. 6). For even lower energies (postacceleration of molecular ions) shuntimpedances of up to 1GΩ/m are possible (curves 3, 4 fig. 6).

For the acceleration of 150keV/u CO^+-molecules an individual stem 108MHz high power prototype has been built in Frankfurt[12] (resonator diameter 0.5m, length 1m, drifttube outer diameter 2cm). By using a proper design of drifttubes and stabilizing rods to fix the support stems, we obtained a nearly constant axial field distribution and a bare shuntimpedance of η_0 = 700MΩ/m, which agrees well with the calculated value. This resonator requires less than 15kW RF power for a total cavity voltage of 3MV.

For the acceleration of ion beams between static or RFQ injectors and Alvarez structures e. g. radial intank focusing is necessary. Even if permanent quadrupole magnets will be used, the drifttube diameter cannot be chosen smaller than approximately 8cm. For an energy range of 0.5-7 MeV/u (curves 4, 5 and upper energy part of curves 2, 3 fig. 6) highly efficient intank focused IH-structures instead of Alvarez and Wideroe structures can be realized.

Since the shuntimpedance depends on the diameter of the support stems a slight increase of the efficiency can be obtained by using massive common bars as drifttube support (Munich postaccelerator, fig. 6).

Even for extremely high capacitive load by large drifttubes, effective shuntimpedances of some 10 MΩ/m are possible[9]. Therefore IH-structures are well suited as RF resonators for MEQALAC (Multiple Electrostatic Quadrupole Array Linear Accelerator)-systems. In such systems a simultaneous acceleration of multiple parallel high current ion beams is possible, even for particle energies as low as ion source extraction voltages.

In order to proof this idea, a MEQALAC-IH-system to accelerate 4 He+-beams from 40 to 106 keV with an average current of 3 mA per channel is to be established at the FOM-Institute, Amsterdam, in cooperation with Frankfurt[13,14].

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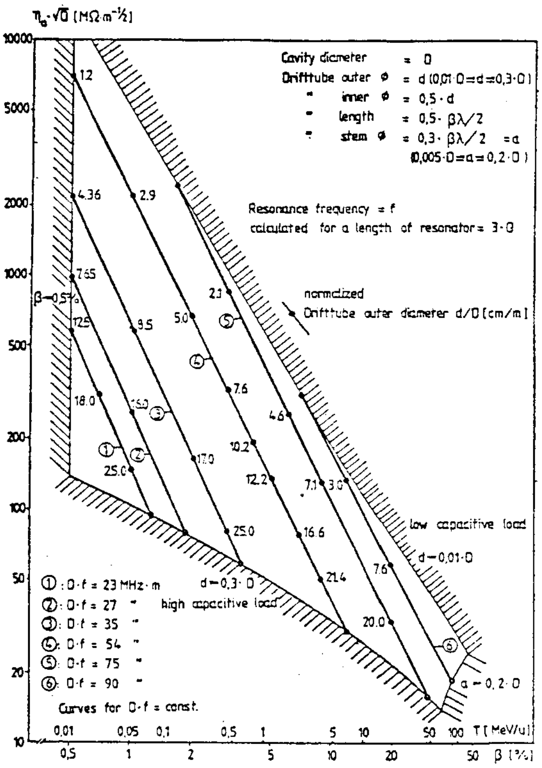

Fig.5 Calculated bare shuntimpedance of IH-structures versus particle energy

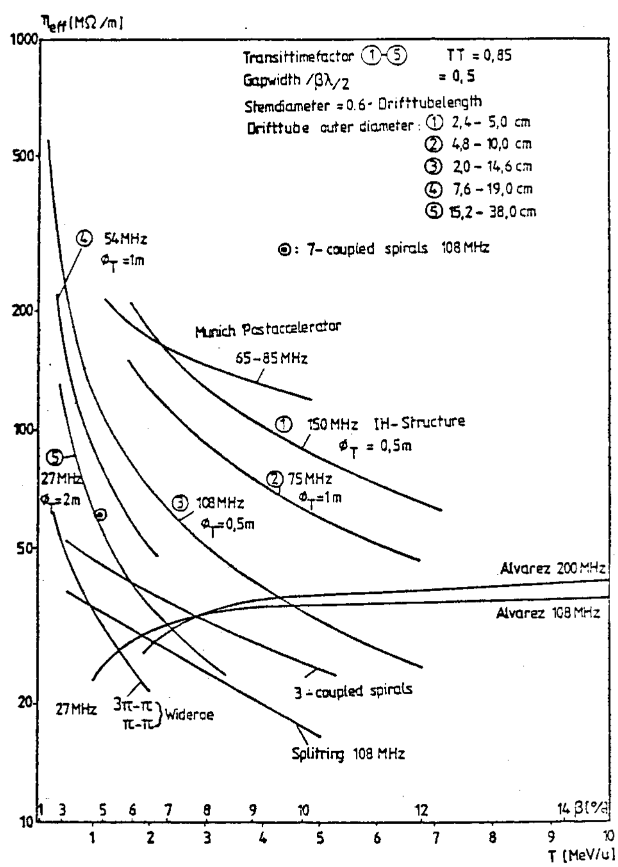

Fig.6 Comparison of different linac structures