MULTIPLE BEAM COUPLED CAVITY CONCEPT AND STRUCTURE

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1. BACKGROUND AND INTRODUCTION

An idea of building microwave linear accelerators in a frequency range close to and beyond 10 GHz has lately become very popular both for high energy and portable accelerators. However, difficulties of this “state-of-the-art” technique such as manufacturing and tuning of microwave cavities become much more complicated at 10 GHz and higher compared to S and L band [1].

Operating at higher frequency permits a reduction in outline dimensions and weight of the final package. However, in higher frequency ranges one faces a problem of beam current restriction among a number of other complications.

A simplified interpretation of a traditional microwave (MW) structure with off-axis or on-axis coupling is shown in Fig.1. These or similar structures are used in linear accelerators or MW power amplifiers - traveling wave tubes, klystrons, etc.

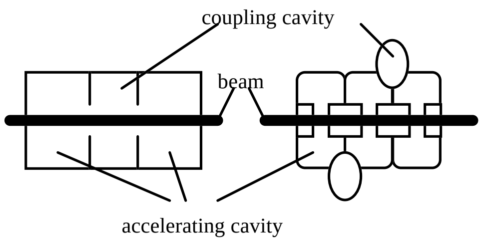

Fig.1 On-axis and off-axis coupled standing wave structures

In an accelerator, the beam passes each cavity and interacts with the axial electrical field in each cavity so that particle energy increases from cavity to cavity, absorbing some amount of MW power.As an example, we will use a standing wave to study MW fields and beam propagation in accelerating mode. An approximation for micropulse or continuous beam current (I) versus relative aperture radius (a/λ) and wavelength value (λ) could be written as follows [2]:

$$I = 0.4 \times (a/\lambda)^2 \times (\lambda)^2 \quad . \qquad (1)$$

For the applicable relative aperture range defined by a/λ =0.05..0.2, beam current roughly equals

$$I = (0.001...0.01) \times (\lambda)^2 \quad . \qquad (2)$$

Beam current is restricted by physical aperture size due to space charge limitation. In commonly used structures it is difficult to exceed the above mentioned values without affecting structure efficiency and energy gain.

One of the possible ways to increase beam current and keep the aperture in the accelerating channel small enough not to reduce the accelerating gradients is to use a resonator with multiple beams. It has been done in the past for multibeam klystron development[3], for example. However, the apertures are located in the same cavity, so it becomes more complicated to apply this approach at higher frequency.

2. MULTIPLE BEAM STRUCTURE (MBS)

2.1 Parallel Circuit Concept Applied to Microwave Structure Analysis

Let us use some very simple considerations to analyze a circuit with various sets of resistors in order to explain the concept and the way it is applied to microwave circuits.

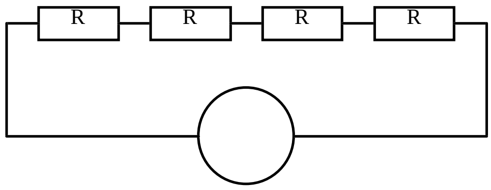

Fig. 2. Set of four sections in series. Total beam voltage U, current - I.

Any microwave structure with propagating beam could be interpreted as an impedance Rs with current I at some certain voltage U. Reactive beam component is not shown separately. Set of four resistors in series shown on Fig.2 represents four sections of linac structure of the same length L and integral shunt impedance R .

For a first approximation, maximum energy gain W_{max} in the four- section microwave structure represented by the circuit shown above is equal to

$$W_{max} = (4*R*P)^{1/2} = 2(R*P)^{1/2} \qquad (3)$$

where R=Rs*L - integral shunt impedance of each segment of microwave structure;

P - microwave power dissipated in the structure.

The load line in this case is

$$W = W_{max} - 4Ib*R = 2(R*P)^{1/2} - 4Ib*R \ . \qquad (4)$$

Now consider combining four segments of the structure in parallel as shown on Fig. 3 transmitting the same current through every structure segment.

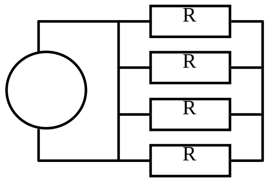

Fig. 3. Set of parallel microwave structure segments.

Assuming that for the parallel circuit R_{par}=R/4,

$$W = W_{max} - 4Ib*R = (R*P)^{1/2} - Ib*R \,. \qquad (5)$$

The length of accelerator section is reduced by a factor of four, which, in turn, reduces maximum energy by a factor of 2 while loading factor is a quarter of the previous value. Maximum current value described by equations (1) and (2) is now increased by the same factor of four.

MBS Load line could be written as

$$W = Wmax/N^{1/2} - I*K/N, \qquad (6)$$

where: K is beam loading coefficient, MeV/A;
N is number of beam lines.

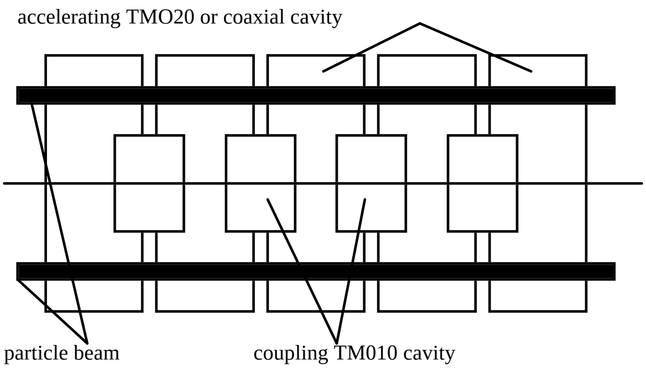

Fig. 4. On-axis coupled structure with a hollow or multiple beam which could be used for accelerator.

The coupling cavities are removed from beam axis, so that they do not reduce the structure shunt impedance and, at the same time, they maintain p/2 phase shift per cavity, comfortable for structure operation. Phase shift between accelerating cavities is equal to p. Outside diameter of the structure remains constant along the length of accelerator. Axial symmetry is important for cavity manufacture, tuning and handling. Coupling coefficient could be made fairly high to reduce filling time of the structure. One could use electrical or magnetic coupling for this design and maintain proper phase shift and maximum shunt impedance value.

2.2 MBS Design Examples

MBS structure could be formed by combination of parallel structures formed by conventional TM_{010} cavities, coupled to each other by common “side” cavities, which in this case are positioned on the central axis of the formed structure.

Example of Four Beam Structure (FBS) formed by combination of four beam centerlines with common coupling cavities shown in Fig.5. Section of linear accelerator is divided into four segments as described above using an electrical circuit concept. Accelerating cavities in a “ring” may or may not be coupled together.

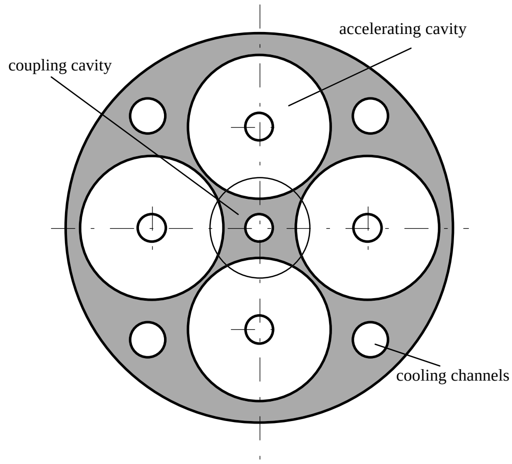

Fig. 5 Four Beam Structure (FBS).

Proposed concept and design could be called "inside-out" version of conventional side coupled structure, shown in Fig.1. Design for a magnetically and electrically coupled standing wave accelerator structure using TM_{020} accelerating cavities and TM_{010} type coupling cavities, located on axis of the structure is presented on Fig.6 and Fig.7, respectively. If the structure is electrically coupled, the axial part would look similar to disk loaded waveguide (DLWG).

The accelerated particle beam is a quasi-uniform hollow beam or a multiple beam.

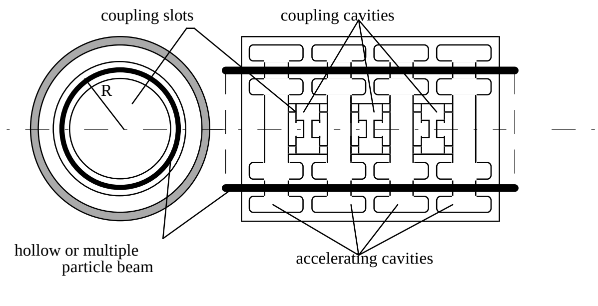

Fig. 6. Magnetically Coupled MBS.

Beam cross section at radius R is shown as quasi-continuous, though it could be built of multiple small apertures.

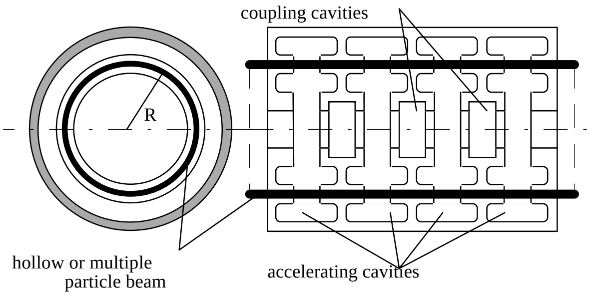

Fig. 7. Electrically Coupled MBS.

The approximate beam current increase is estimated as k= pR/a, where R is radius of a ring-type aperture for the new structure. Possible beam current increase could vary approximately from 10 to 20.

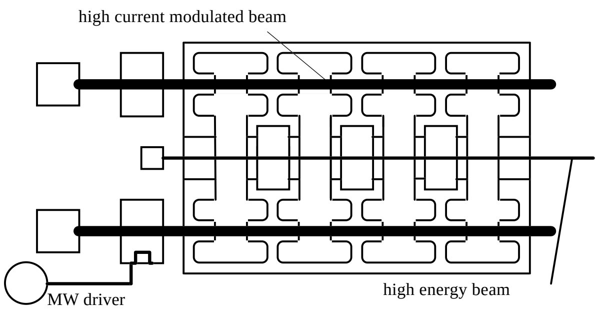

Fig. 8. Beam Excited Configuration

Beam excited configuration is one of the possible practical realizations of the design (Fig. 8). High current, low energy, modulated beams which propagate through the off-axis apertures would induced on-axis electrical fields which could be used for low-energy beam acceleration.

This design is a combination of MW amplifier and accelerator. We believe that the described approach could substantially reduce the overall system size and mass. Currently, similar systems are of high interest at particle beam research facilities [4,5].

3. CONCLUSIONS

Beam current is restricted by physical aperture size due to space charge limitation and, in commonly used structures, it is hard to exceed the above mentioned values without affecting structure efficiency and energy gain. Multiple or hollow beam concept of microwave structure design is proposed to expand range of current which could propagate through the structure. In our study, the coupled circuits model and microwave theory was used to analyze one of the basic cases of the proposed concept. A cavity was designed which is capable of accelerating four parallel beams, the tuning procedure was refined and microwave properties of the structure were studied [6]. The study could be considered successful as our analysis confirmed predictions made at the very early stage of development.

We have proposed a “turn-key” prototype linac using a miniature 12 cm long FBS and a 1.5 MW X-band magnetron as a power source. Performance goal for the electron beam head is to operate at beam energy of 1.2 MeV and beam peak current of 1 A with no external focusing, providing, therefore, around 1 kW average power stored in four beams at 0.001 duty factor [7]. The proposed design concept could be used in high energy radiography, computer tomography, intraoperative surgery, neurosurgery, radiation therapy, geophysical logging, sterilization, space technology, high energy physics and any other application for high energy X-ray or electron beam equipment.

4. REFERENCES

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