TRAVELING WAVE LINEAR ACCELERATOR WITH RF POWER FLOW OUTSIDE OF ACCELERATING CAVITIES*

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Abstract

An accelerating structure is a critical component of particle accelerators for medical, security, industrial and scientific applications. Standing-wave side-coupled accelerating structures are used when available rf power is at a premium and average current and average power lost in the structure are large. These structures are expensive to manufacture and typically require a circulator; a device that diverts structure-reflected power away from rf source, klystron or magnetron. In this report a traveling wave accelerating structure is presented, which combines the high shunt impedance of the side-coupled standing wave structures with the advantages of traveling wave structures, such as simpler tuning and manufacturing. In addition, the traveling wave structure is matched to the rf source so no circulator is needed. This paper presents the motivation for this structure and shows a practical example.

INTRODUCTION AND MOTIVATION

Physics and technology of rf accelerating structures is a mature field with variety of existing geometries and methods. To distinguish a new approach from existing ones, first we will discuss accelerating structures used for the same applications. In this discussion we will emphasize the disadvantages to be improved upon using this new accelerating structure.

Side Coupled Standing Wave Accelerating Structure

In Fig. 1 a cell of a typical side-coupled standing wave (SW) accelerating structure is shown. This type of accelerator is widely used in medical, industrial and security applications because it offers very high shunt impedance and operational stability [1, 2]. For example, this high shunt impedance permits positioning of the complete accelerator on the arm of a robot for radio-surgery [3].

This accelerating structure is a bi-periodic system that works at the $\pi/2$ resonant mode. the structure made up of of accelerating and coupling cavities. In the working mode, most of the electro-magnetic fields are in the accelerating cells as seen in Fig. 1. The cavities are coupled magnetically with the coupling slots located near the outer diameter of the accelerating cavity.

Electron beam deflection The coupling slots in the side-coupled SW structure are located asymmetrically with respect to the axis where electrons or other charged particles are accelerated. This asymmetry, as well as power flow

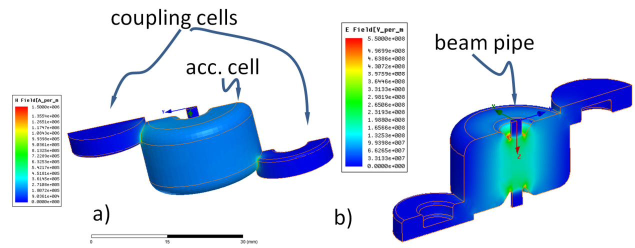

Figure 1: Finite element model of a half-cell of a side-coupled standing wave accelerating structure. Surface fields are normalized to 100 MV/m accelerating gradient: a) magnetic fields with peak magnitude of ~1.5 MA/m; b) electric fields with peak magnitude ~550 MV/m. This electromagnetic simulations were performed using a commercial finite-element code HFSS [4].

through the accelerating cell, creates electric and magnetic fields deflecting the beam off its axis. This deflection distorts the beam, especially during initial stages of acceleration, increasing beam losses and creating an uneven pattern on the x-ray target thus reducing the performance of the system.

Complexity of tuning and manufacturing The side-coupled SW structures are typically brazed in pieces, where each piece includes one half of accelerating cell and one half of coupling cell. When joined, two such pieces create the cavity shown in Fig. 1. The complexity of the joint's surface complicates the brazing so each cell has to be significantly tuned. The tuning is done to insure the desired field profile and make the frequencies of coupling and accelerating cells the same. The tuning is made difficult by the small fields in the coupling cell. This low field prevents tuning of this cell while in working configuration, so the cell typically has a hole to insert a measurement probe or perturb the cavity volume. This complexity both increases manufacturing and tuning cost and makes it difficult to evaluate the quality of the tuned structure.

Protection of RF source from reflected power By its nature of being a resonant cavity, a standing-wave structure absorbs rf signals in a narrow frequency band. For higher efficiency, the rf loss in the structure has to be as small as practical. The lower the rf losses, the narrower the frequency response of the structure. During initial transient, when such a narrow-band structure is filled with rf power, most of the power is reflected. If this reflected power does propagate back to the rf source, it will degrade its performance or may damage it. To protect the rf source, a waveguide isolator (typically a circulator) is installed between the SW accelerating structure and rf source. The isolator attenuates precious

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RF power in the forward direction, and increase complexity and cost of the linac.

There is an alternative solution to this problem of narrow-band reflection. Several standing-wave structures could be connected using a waveguide hybrid so the combined reflection is directed away from the rf source toward an rf load. This solution also increases complexity and cost of the system: one will need at least two accelerating structures, a waveguide hybrid and an additional set of waveguides.

Traveling Wave Accelerating Structures

Traveling wave (TW) structures are mature technology. SLAC linac has 2-miles of them [5]. They are typically axisymmetric so they do not deflect the accelerated beam (assuming they use input couplers with symmetrized fields). All accelerating cells are filled with electromagnetic fields, so their tuning process is simpler than tuning of side-coupled SW structures. TW structures are matched to the rf source, and so they do not need a waveguide isolator or circulator.

With all these advantages, the TW structures are not used in compact linacs because they have low shunt impedance. The increase of the shunt impedance is limited by the fact that rf power flows through each cell of the structure. To sustain this flow, coupling apertures cannot be reduced below a certain size. At the same time, the reduction of the aperture increases shunt impedance. As a result the shunt impedance of TW structures is 30-50% lower than that of side coupled standing-wave structures.

Another disadvantage of the TW structures is related to the rf power flow. The whole power passes through the first accelerating cell. The higher the power flow, the higher the probability of rf breakdowns [6, 7].

Parallel Coupled Standing Wave Structures

To improve performance of standing wave and traveling wave structures accelerating structures with parallel coupled cavities were developed [8, 9]. Specifically, this approach eliminates power flow through the accelerating cell in order to decrease rf breakdown probability [10–12].

However, these structures are significantly more complex in construction and tuning in comparison with both traveling-wave structures and side coupled standing-wave structures.

Similar to side-coupled SW structures, the field inside the accelerating cells deflects the particle beam, and, as with other standing wave structures, they need a waveguide isolator or additional waveguide components to protect the rf power source.

TRAVELING WAVE STRUCTURE WITH POWER FLOW OUTSIDE OF ACCELERATING CAVITIES

Here we introduce a new type of accelerating structure which combines high shunt impedance of the side-coupled SW accelerating structure with the beneficial properties of a traveling wave structure. Such a structure is shown in Fig. 2. It consists of an input waveguide circuit (2, 3, 4, 5, 6); input matching cell (9); set of regular cells (10); output matching cell (11); and output waveguide circuit. We note that the structure shown in Fig. 2 demonstrates the concept, it is by no means the only possible implementation of the method. Possible modifications include replacing the input waveguide circuit with any other symmetric feed; replacing output circuit with two rf loads; and *etc*. A structure built according to this method could be designed with a field profile that accelerates electrons from low energy of ~10 keV to serve as a drop-in replacement for a side-coupled standing wave structure.

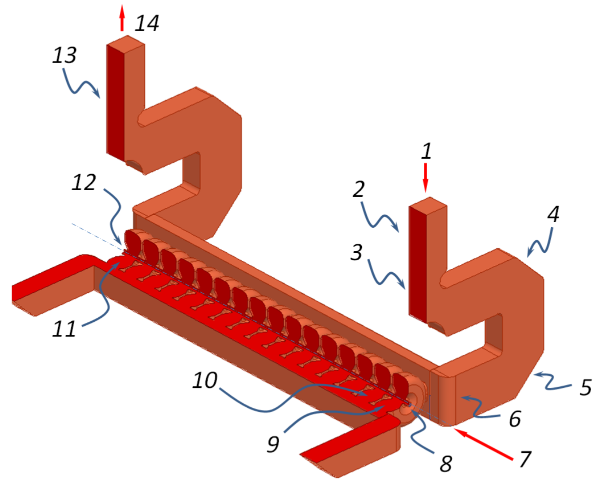

Figure 2: Schematic view of the vacuum region of the proposed TW accelerating structure. Upper left part is cut to show internal geometry. The scale is for 9.3 GHz , $2\pi/3$ phase advance structure. Notation as follows: 1–input RF power; 2 – input waveguide; 3 - matched 3dB splitter; 4, 5 – matched H plane bends; 6 – matched E-pane bend; 7 - direction of electron beam; 8 – input beam pipe; 9 – input matching cell; 10 – first regular cell; 11 – output matching cell; 12 – output beam pipe; 13 – output waveguide; 14 - output RF power.

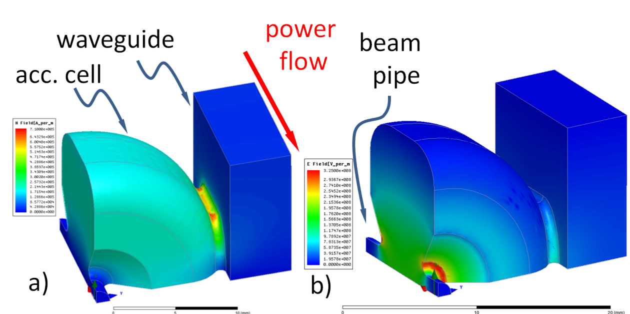

Figure 3: Quarter-cell finite element model of the proposed traveling wave accelerating structure. Surface electric fields are normalized to 100 MV/m accelerating gradient: a) magnetic fields with peak magnitude of 0.71 MA/m; b) electric fields with peak magnitude ~325 MV/m.

The proposed structure is designed with the same approach as traditional forward-wave and backward-wave TW

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structures. One period of it is shown in Fig. 3. This period consists of an accelerating cell and a waveguide that transmits power between the accelerating cells.

The accelerating cell has a nose-cone in order to increase the shunt impedance. The nose cone cuts-off field propagating into the beam pipe and therefore all power flows along the structure in the outside waveguide. The structure is symmetric with respect to the beam axis, so it has no dipole field component deflecting the beam. Remaining quadruple components could either be used to focus the beam or eliminated by slightly distorting accelerating cell shape.

The key distinction between this structure and either side-coupled, on-axis coupled or parallel-coupled SW structures it that the wave travels in it with significant group velocity. In this property it is similar to traditional on-axis-coupled TW accelerating structures, but without the drawback of low shunt impedance or increased rf breakdown probability due to rf power flow through accelerating cavity.

The simulations show that this new TW structure has single operating mode, as seen in Fig. 4, where the dispersion diagram for the period from Fig. 3 is shown. As seen in Fig. 4(b), at the working point ($2\pi/3$ phase advance per cell), only the operating mode is propagating. The lower dipole mode is propagating at operating frequency with ~85 deg. phase advance per period. We speculate that since this dipole mode is not excited by symmetric input coupler and its effect on linac performance will be manageable.

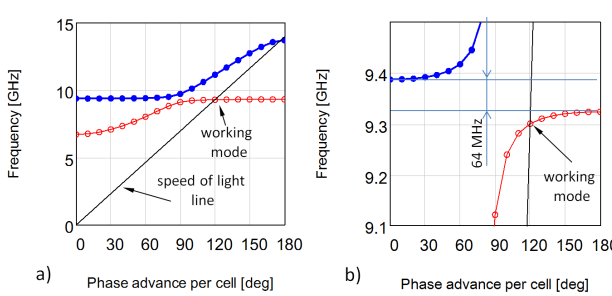

Figure 4: Dispersion diagram for one cell of the TW structure shown in Fig. 4: a) full frequency span with two lowest brunches; b) 400 MHz frequency span.

In Table 1, we show a quantitative comparison between a typical side-coupled standing wave structure and the proposed traveling wave structure shown in Fig. 3. Both structures will accelerate an ultra-relativistic beam moving with close-to-speed of light velocity. As seen in the table, both structures have practically identical shunt impedance. At the same time the new TW structure has lower peak surface electric and magnetic fields, stored energy and power lost per cell. We speculate that with other advantages brought by use of traveling wave and symmetric feed, linacs built with this type of accelerating structure will have superior performance to commonly used side-coupled and parallel-coupled standing wave structures.

Table 1: Comparison between parameters for the proposed traveling-wave structure and those of a typical side-coupled standing wave structure. The structures were simulated using HFSS [4].

Parameter	**TW**	**SW**
Cell length [mm]	10.745	16.104
Aperture radius, a [mm]	1.14	1.14
a/λ	0.035	0.035
Frequency [GHz]	9.3	9.3
Q-value	6802	7917
Phase Advance per Cell [deg.]	120	180
Phase Velocity [speed of light]	1.0	1.0
Group Velocity [speed of light]	0.013	0
Attenuation Length [m]	0.47	-
Shunt Impedance, R [MOhm/m]	144	143
R/Q [kOhm/m]	21.27	18.1
Accelerating Gradient [MV/m]	100	100
RF Power Flow [MW]	32.25	-
Peak Electric Field [MV/m]	325	550
Peak Magnetic Field [kA/m]	710	1500
E_{max}/E_{acc}	3.25	5.5
$H_{max}Z_o/E_{acc}$	2.7	5.7
RF Losses per Cell [MW]	0.74	1.12
Stored Energy per Cell [mJ]	87	152

RF Breakdown

During operation of an accelerating structure, vacuum rf breakdowns degrade and disrupt the structure performance. There is overwhelming experimental evidence that increased rf power flow increases the probability of rf breakdowns [6, 7]. The breakdowns originate in accelerating cells which have high electric and high magnetic rf fields. In structures where rf power flows through the accelerating cells, a significant portion of the rf source power could reach the breakdown site thus increasing probability of breakdowns. In both on-axis coupled TW structure and side-coupled SW structure the power flows through the accelerating cells. In the new structure rf power will be diverted from the cell where the breakdown occurred to the side waveguide therefore improving its high gradient performance.

SUMMARY

A novel traveling wave accelerating structure is introduced [13]. It has the high shunt impedance of a side-coupled standing-wave accelerating structures, but without the drawbacks. It does not need a waveguide isolator, has no deflecting on-axis fields or power flow through the accelerating cell, and it is simple to tune and characterize electrically. We suggest a practical method of manufacturing of the structure by precision milling it out of two halves, similar to X-band structure described in [14]. The structure could be used in compact high repetition rate medical and industrial accelerators.

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