NOVEL ACCELERATION STRUCTURE USING SLOT RESONANCE COUPLING*

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Abstract

We have explored the use of slot resonance as a building block for coupled cavity circuits for use in standing-wave electron and ion accelerators. The technology can be applied to proton/ion linacs in the velocity range β between 0.2 and 0.5. The idea is harder to apply in the case of electron linacs (β~1) because of a sign flip in the coupling mechanism relative to a side-coupled linac (SCL). Several methods of getting around this limitation are presented, ending with a description of a breakthrough that was made during the course of the study, the idea of dual slot resonance linac (DSRL). This coupling method results in a linac that is more compact than an equivalent SCL, and has equivalent or better shunt impedance.

INTRODUCTION

Popular choices of standing-wave linac technologies include the drift tube linac (DTL), the side-coupled linac (SCL), and hybrids of the two for proton acceleration, and short π-mode sections as well as the SCL and bi-periodic structure for accelerating electrons. The commonality between these technologies, with the exception of π-mode structures, is the use of a π/2 phase advance between resonators. The DTL uses a set of stabilizing ~λ/4-long rods to achieve this, which take the place of the side coupling cells in an SCL, or the longitudinally compact coupling cells in the bi-periodic scheme. The use of π/2 phase advance is advantageous because the structure is operated in a region of maximum steepness of the dispersion curve, and therefore achieves a maximum frequency separation between the operating mode and the next nearest structure eigenmode. This allows for a longer linac section to be fed from a single RF input port. Operation in π/2 mode is also used to amplitude- and phase-stabilize a long structure. The input power, as well as any imbalanced fields within the structure can easily flow to the desired structure mode pattern via the π/2 forward and backward travelling wave modes.

Slot resonances are known to designers of traveling wave tube (TWT) RF amplifiers, with the slots being used to couple adjacent cavities together. Typically, these devices are tuned in such a way as to create two distinct transmission bands, one being the slot band, and the other being the cavity band. TWT's can be designed with the slot band being either below or above the cavity band in frequency to achieve different sets of design goals.

Operation of a linac structure in π/2 phase advance mode requires the two bands to be tuned so that they merge into one, with a minimum (or non-existent) stop band in between, and thus achieve a closed dispersion curve. This is beneficial because it retains the property of maximum steepness of the dispersion curve at the operating frequency. A sizable stop-band will have zero slope in the dispersion curve, and, in extreme cases, will have disadvantages similar to that of a π-mode structure.

In the design phase, a closed dispersion curve is achieved by considering the resonator frequencies, as well as the nearest neighbor and next-nearest neighbor coupling coefficients. In an SCL, an on-axis cell couples to each of its two side cells (nearest neighbor), but there is also coupling between the two side cells (next-nearest neighbor). This is compensated by tuning the side cells to a slightly different frequency than the on-axis cells. In the fabrication phase, each cell in an SCL typically has some tuning mechanism which can be adjusted to achieve the desired dispersion curve and field balance of the structure.

One of the figures of merit for accelerator structures is the shunt impedance per unit length, or ZTT, where T is the time transit factor. An optimized single cell is typically λ/2 long, has a nose cone to improve T, and has a rounded, nearly spherical, shape of the outer wall. When a SCL is required to accelerate lower-velocity species, the available longitudinal space for the cell is diminished below βλ/2, and the cell shunt impedance drops. At some value of β, typically at β=0.4, it becomes more efficient to double the length of each cell, resulting in half the number of gaps per unit length, as in a DTL.

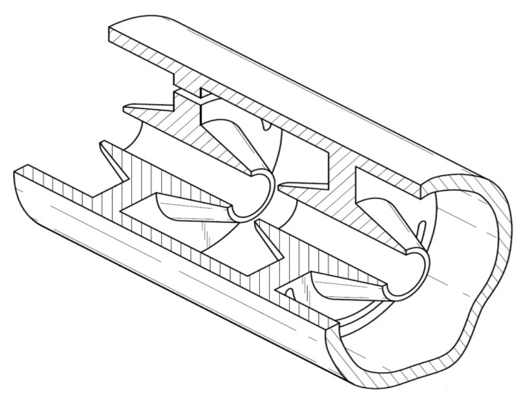

Figure 1: Slot resonance linac structure. Each slot extends nearly 180° in azimuth.

PROTON ACCELERATION

Slot resonance coupling can be applied to proton linacs in the range of $0.2 < \beta < 0.4$ with the scheme pictured in Fig. 1. In this Figure, the length available for each cell is βλ long, and the slots are staggered azimuthally to avoid a dipole contribution. The mode has all the gap electric

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fields pointing in the same direction, similar to a DTL. The structure in Fig. 1 does not use an optimized geometry, and was only used to demonstrate that a closed dispersion curve could be achieved. Each slot covers a nearly 180 degree azimuthal angle, corresponding to the slot length being about $\lambda/2$.

The advantages of slot resonance coupling include: 1) The losses associated with the slots is much smaller than for an equivalent SCL case, 2) the slot does not increase the number of parts required to make the structure, and 3), as the slot resonance frequency depends on the length of the slot, there is hope that the slot can be fabricated without a tuning device since the shape of the slot will likely not change during structure fabrication and brazing. We have also noticed that resonant slots provide a very large amount of coupling between cells, around 30%. This is much larger than typical side-coupling cell designs. The increased coupling diminishes structure fabrication tolerances.

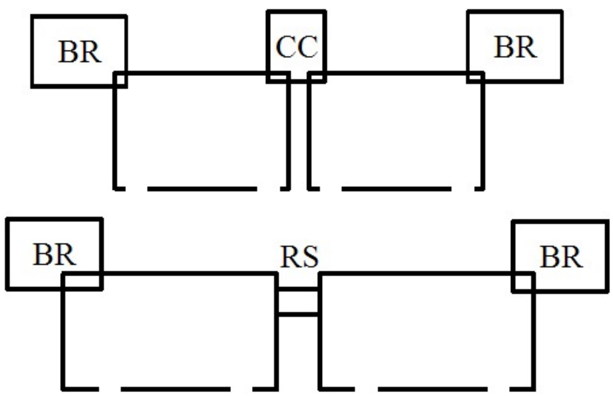

Figure 2: CCDTL (top) and slot-coupled scheme (bottom), including bridge cells (BR), coupling cells (CC), and resonant slot (RS). Each spoke cavity has two gaps, shown above as discontinuous lines.

Slot resonance coupling also introduces a sign change in the coupling between adjacent on-axis cells vs. side coupling cells. This can be understood in terms of the magnetic field patterns of a slot and a side coupling cell in each adjacent on-axis cell. The mode in a side-coupling cell exposes a magnetic field having the same vector direction at each coupling slot. In contrast the magnetic field of the slot mode wraps around the middle of the slot and changes sign in the location of each on-axis cell. Because of this, resonant slots are only useful in a structure mode where adjacent on-axis cells have their fields pointing in the same direction.

The design of any high-current proton linac is strongly influenced by the type of magnetic focusing channel needed to propagate the beam through the structure. A quadrupole magnet can be accommodated within the structure by using a “bridge cell” to divert the RF power around the magnet. Each bridge cell takes the place of a resonant slot, and therefore makes the entire structure look less like the pure slot resonance design pictured in Fig. 1.

We have compared a slot-resonance scheme using bridge cells with one such accelerator [1] using the SCDTL (side-coupled drift-tube linac) configuration used in for $0.2<\beta<0.4$ in the SNS linac. The SCDTL structure consists of a set of spoke cavities operated in 0-mode, where the coupling between adjacent spoke cavities alternates between a side coupling cell and a bridge cell, as shown in Fig. 2. The gaps in each spoke resonator are located very close to the ends of the cell, making the cell length 1.5λ. In order to use the slot resonance idea in a similar accelerator structure, the length of each spoke cavity should be extended to 2λ, as shown in the bottom of the same Figure. This allows a more efficient cavity design to be used for the spoke resonator, at the expense of having fewer gaps per unit length, and longer distance between quadrupole magnets. The shunt impedance of the slot resonance structure is competitive with the SCDTL. There are likely to be applications where the decreased complexity of the slot resonance coupling offsets the trade-offs in the magnetic lattice.

TOWARDS HIGHER BETA

$2\pi/3$ Structure

We have explored several methods for extending the slot resonance idea to higher β. One such idea is the use of a $2\pi/3$ mode. The coupling is alternately done by resonant and non-resonant slots. In order for such a mode to be synchronous with the beam, the gaps are offset from the center of each cavity, resulting in $\beta\lambda$ distance between gaps separated by a resonant slot, and $\beta\lambda/2$ between gaps separated by a non-resonant slot. However, the non-resonant slots must be made large enough to provide nearly as much coupling as the resonant slots. In this configuration, the non-resonant slots tend to dissipate too much RF power. We did not perform a detailed design of the $2\pi/3$ structure beyond a simple conceptual design.

Interleaved Structure

A slot resonance coupled structure can also be made into an interleaved structure with two channels connecting the even and odd set of accelerator cells. However, the slot should be made much deeper than what has been discussed above. As the slot depth increases, it begins to resemble a waveguide operated near the cutoff frequency. A geometry simulated in HFSS [2] for this structure is shown in Fig. 1. As the waveguide length is increased, the mode near cutoff and the next higher mode become closer in frequency. Off resonance excitation of the higher order mode can waste some power, making this scheme roughly equivalent to the side-coupled case with 15% losses due to coupling. An advantage of the interleaved structure is that, since there are two channels belonging to the even and odd cavities, the structure can be twice as long and still maintain acceptable RF requirements.

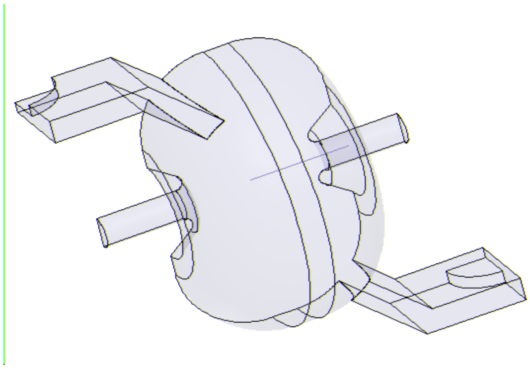

Figure 3: One cell of an interleaved structure.

A related concept to the 2π/3 structure and the interleaved structure is a structure operated in π/2 mode, but with an extra cell coupled with non-resonant slots to the main cells. The topology is shown in Fig. 3. Unlike the 2π/3 phase advance structure, the non-resonant coupling in this scheme can be much weaker than the resonant waveguides linking the "regular" cells. A MATLAB model was developed to predict the dispersion diagram of such a structure. The stored energy of the weveguide and cell modes are very different vs. the magnetic field strength in the coupling volume, so the coupling is asymmetric, which is implemented in the model. This system has, in general three passbands, where two can be merged together by a proper choice of cell resonant frequencies to achieve the desired acceleration mode.

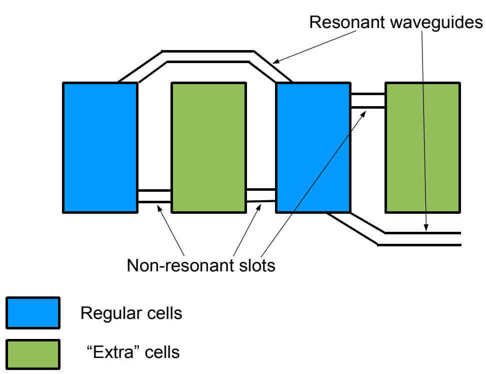

Figure 4: π/2 structure with extra cell.

DUAL SLOT RESONANCE LINAC

The dual slot resonance linac scheme is able to achieve a high shunt impedance design in a very limited radial space. This is unlike the previously discussed waveguide-coupled idea, which needs additional space for locating the waveguides. When two slots are in close proximity to one another, their magnetic fields will strongly couple, resulting in two modes where they oscillate in phase and out of phase, and the two modes will have different frequencies due to the coupling, with a frequency ratio exceeding 2:1. In our scheme, we envision one slot to be between one acceleration cavity and a small void, and the second slot to be between that space and the next cavity, as shown in Fig. 5. HFSS simulations of this structure have demonstrated that a closed dispersion curve can be achieved by a proper choice in slot geometry.

The triangular void used as coupling between adjacent resonant slots naturally fits between the curved outer surfaces of optimized accelerator cells. This results in a very compact geometry, with only a slight increase in radius beyond the cells.

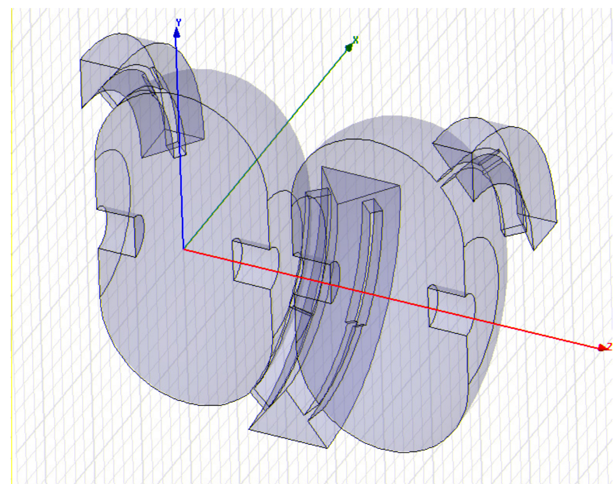

Figure 5: Dual slot resonance linac. A simplified model for the nose-cones was used to improve the meshing of the rest of the problem.

CONCLUSION

The slot resonance coupling concept has been developed for the case of proton and electron linacs. The slot resonance coupling concept has been developed for the case of proton and electron linacs. The DSRL scheme has many advantages: compactness, ease of fabrication, competitive shunt impedance, etc. It is a good design for a medical or industrial linac. We have applied for a follow-on SBIR contract to build and install an accelerator structure based on the DSRL concept as an energy booster for the UCLA Pegasus laboratory.

REFERENCES

[1] J.H. Billen and H. Takeda, "RF Structures and Beam Dynamics Design for the Spallation Neutron Source", SNS Note SNS-104050300-TR0013-R00.

[2] HFSS, version 9.1, Ansys Corp.