A NEW ACCELERATOR STRUCTURE CONCEPT: THE ZIPPER STRUCTURE*

Christopher Nantista, SLAC, Menlo Park, CA 94025, U.S.A.

Abstract
I introduce a novel normal-conducting accelerator structure combining standing wave and traveling wave characteristics, with relatively open cells. I describe the concept and geometry, optimize parameters, and discuss the advantages and limitations this new structure presents.

INTRODUCTION

A number of different geometries have been employed over the years in accelerating structures. Currently, efforts continue toward finding the optimal design for use in a normal conducting TeV-scale electron-positron linear collider. The key general structure parameters of shunt impedance and quality factor relate to the RF-to-beam power transfer efficiency. Also rising to prime importance for a linear collider are the sustainable accelerating gradient, which drives the overall linac length, and the HOM wakefields, which impact beam dynamics and emittance preservation. To maximize the former, generally limited by RF breakdown or pulsed heating, variation of geometrical parameters has been tried, including group velocity, phase advance per cell, and iris tip shape, as well as different materials, surface preparations, and frequencies. Standing-wave structures have also been considered as perhaps offering advantages over traveling-wave structures in regard to breakdown. The deleterious effects of wakefields have been addressed by techniques such as damping into external manifolds, radiating out through chokes or channeling through slots into absorbers.

I present below an idea for a radically different structure with features that may recommend it over perturbations of more conventional geometries. It has not yet been tested, but is currently in the design stage. I will attempt to motivate its conception, describe its features, and suggest reasonable parameters for an X-band prototype.

MOTIVATING CONSIDERATIONS

Large iris apertures, for large group velocity (traveling-wave structures) or mode spacing (standing wave structures), seem to exacerbate breakdown problems. They tend to increase the ratio of the peak surface electric field to the accelerating gradient and reduce shunt impedance. If we decouple power flow/cell coupling from the beam irises, we can keep the latter as small as short-range wakefield considerations allow.

Coupler cells (and those near them) have proven to be particularly prone to gradient limiting RF breakdown. Even if pulsed heating of the waveguide coupling iris is minimized, squeezing the full structure power through such cells seems inadvisable. We can eliminate the bottleneck presented by coupler cells if we couple to all cells identically.

Long range wakefields must be suppressed by removing HOM power deposited by the bunch train. What if all the cells were heavily coupled, with a fairly wide-open geometry, into an easily damped volume? One might then avoid pulsed heating and high electric field problems associated with slots and chokes.

A π/2 phase advance per cell might offer improved R/Q, though perhaps lower Q, compared to larger phase advances, since the cell transit time factor can be significantly larger (0.90 *vs.* 0.64 for a π mode in a simple pillbox). For traveling-wave structures, variations from the 2π/3 traditional SLAC choice that have been tried range from π/3–5π/6. For a standing-wave structure, a π/2 mode leaves every other cell empty, thus killing the effective shunt impedance. This problem is often dealt with by employing a bi-periodic structure with the empty cells either collapsed in length or moved off axis (side-coupled).

What if, instead, we excited the set of empty cells in their own independent resonance π/2 out of phase with the first set, so that the beam is synchronously accelerated throughout?

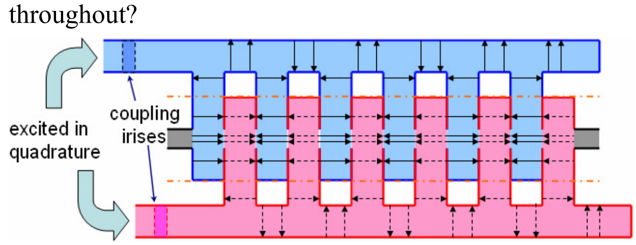

Figure 1: Basic waveguide circuit and field pattern of the zipper structure with degenerate orthogonal resonances driven π/2 out of phase.

THE ZIPPER CONCEPT

Consideration of the above issues eventually led to the zipper-like structure geometry suggested by Fig.1. With normal, axial cell coupling, the tuning of the end cells would determine whether one, the other, or neither π/2 mode was a resonance in the fundamental mode passband of the structure. If the cells are decoupled on axis, or such coupling is overwhelmed by heavy side coupling between sets of every other cell through a waveguide, as shown, one might imagine driving both degenerate resonances.

The structure is essentially a pair of interleaved combs of stubbed waveguide. The regions comprising the actual cells are, as envisioned here, square, rather than axially symmetric. One wall of each cell is removed, perfectly substituted for by a null in the standing-wave field pattern

*Work supported by the U.S. Department of Energy under contract DE-AC02-76SF00515.

of the stub. The alternate stubs are connected at the center of their field lobes by a beam hole.

As the normal guide wavelength in the coupling waveguide is greater than the free space wavelength, coupling periodically to a speed-of-light structure might seem problematic. The key to this solution was extending the stub length between the waveguide wall and the virtual short represented by the null at the missing cavity wall. By adjusting this length, the periodic structure represented by the (short-)stubbed waveguide could be made to have the same phase advance as required by the accelerating structure. (In practice, the phase advance is set by boundary conditions and the stub adjusted to set the frequency.)

Each waveguide comb resonates in a standing-wave π-mode pattern. When excited in quadrature, they present to the beam what appears to be a traveling-wave π/2-mode structure. This "zipper" structure* can thus be considered a virtual- or pseudo-traveling-wave structure.

FEEDING

To obtain the proper relative phase, the two sides of the structure can be powered from a single feed waveguide split through a hybrid or asymmetric magic T. A benefit of this split feeding, is that the reflections from the two sides combine into the fourth port of the hybrid or magic T, which would terminate in a load. The standard technique of pairing up standing-wave structures to isolate the source from reflections this way is not necessary; the structure is itself a pair of resonators.

At the input of each side waveguide, a mismatch can be incorporated into a transition to reduced height to achieve the proper coupling for the desired β. The waveguide, being so strongly coupled to each of its cells, is itself part of the resonant circuit.

In the two waveguide coupling irises and the load port can be seen further similarities to a traveling-wave structure, though they are all at the same end.

CELL DESIGN

After a simulation check of the concept, an attempt was made to develop reasonable, somewhat optimized parameters for an initial 11.424 GHz design. The iris radius was fixed at 2.887 mm, or a/λ at 0.11, following recent CLIC designs [2]. For the zipper geometry, only short range wakefield considerations limit how small this can be. Structure performance can be improved with smaller apertures where applications allow.

As shunt impedance for the square π/2 accelerating region tended to improve with decreasing iris thickness, a value of 0.050" (1.27 mm) was chosen as mechanically feasible. To reduce the peak surface field, the iris tip shape was morphed to an ellipse with an aspect ratio of 3.

The cell side, and thus the waveguide width, came out to be 0.7591". The waveguide height was set at 0.1875" (4.7625 mm), half the height of the WR75 standard. The corners at the stub intersection are points of high electric field and had to also be elliptically blunted (with semi-axes 0.100" along and 0.050" perpendicular to the waveguide) to bring the field down to about the level of that at the iris tips.

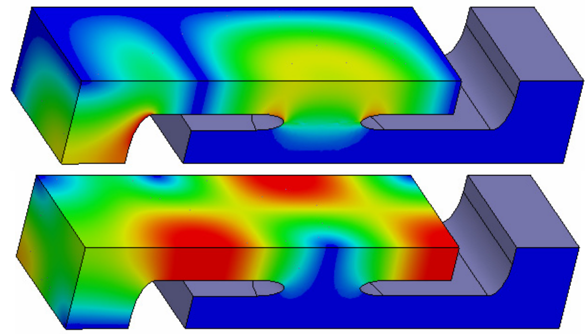

Figure 2: Half geometry of one period from mid-cell to mid-cell. The top image shows the electric field pattern and the bottom one the magnetic field pattern for one of the two symmetric, out-of phase modes.

The resulting geometry of one period of this zipper structure is shown in Fig. 2, along with HFSS plots of the fields for one of the two resonances, solved by imposing electric and magnetic boundary conditions on the top and bottom faces, respectively. The longitudinal cuts here suggest how the structure might be fabricated from machined stack-and-braze cells. Structure parameters were calculated from these field solutions. To account for the other mode, the voltage across this period is doubled, as is the stored energy, so that r/Q (=$V^2/(\omega UL)$) is also doubled.

Table 1: Structure Parameters

Parameter	Zipper 1	Zipper 2	Circ (π) 1
f_r (GHz)	11.424	11.424	11.424
a/λ	0.11	0.11	0.11
r/Q (kΩ/m)	10.90	11.73	11.28
Q_0	6,370	6,193	8,949
r (MΩ/m)	69.41	72.65	100.9
E_p/E_a	1.75	1.98	3.20
η_{CLIC}	0.2831	0.2964	0.3310

Structure characteristics are listed in Table 1 (Zipper 1). The last row gives the calculated RF-to-beam efficiency,

$$\eta \equiv \frac{T_b}{T_f + T_b} \frac{I_b G}{P_{RF} / L}, \tag{1}$$

using the CLIC parameters: I_b=1.192 A, T_b=155.5ns, and G=100 MV/m [1]. T_f is the fill time and P_{RF}/L the input power per unit length. These are set, along with β, to give flat acceleration and zero reflection during the beam.

* This name, previously applied to an unrelated W-band structure (see Kroll, *et al.*,"PLANAR ACCELERATOR STRUCTURES FOR MILLIMETER WAVELENGTHS," PAC '99), is appropriated with the permission of the late Prof. Robert H. Siemann.

A second design was made with the focus more on increasing efficiency than minimizing surface electric field. The iris was thinned slightly to 0.045" (1.143 mm), with the tip blended into a 0.0522" (1.326 mm) diameter bulb. This allowed the side to be held at exactly 0.750" (19.05 mm) to match WR75. The side waveguide was slightly reduced in height to 4 mm to reduce stored energy, and the stub corner rounded to 1.5 mm.

The characteristics of this design (Zipper 2) are also shown in Table 1. For comparison, a third set of values is given for a circular π-mode standing-wave cell of the same iris as the first zipper design. This standard structure wins here in efficiency, but at the cost of much higher surface field. Further, it has no HOM damping and would be limited in length by narrow pass band. The latest traveling-wave CLIC structure has an efficiency of 0.277 [1].

Based on calculated 0-π mode frequency separation for the two regions, the period-to-period coupling of the stubbed waveguide region of the first design was found to be ~16.4 times greater coupling than that of the square cell region (k=0.197 vs. 0.012) and should dominate. An S-parameter simulation using two periods to eliminate the need for an artificially imposed magnetic boundary verified isolation between the two side waveguides of better than -30 dB. This decoupling of the combs without the need for cell-isolating nose cones is required by field symmetry, as well as by the fact that the π/2 mode leaves every other cell empty.

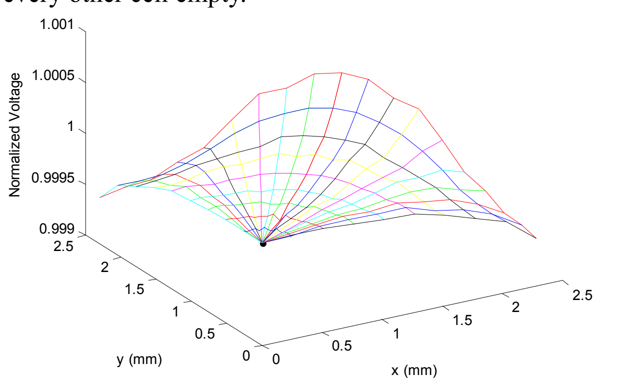

Figure 3: Integrated acceleration as a function of transverse displacement from the axis calculated from HFSS fields.

ACCELERATION FLATNESS

To avoid HOM-trapping constrictions and for symmetry with the standing wave electric field null, the effective accelerating cell region in the zipper structure is given a square shape. For a standard structure with circular cells, it can be shown that the longitudinal acceleration experienced by the beam is constant across the iris aperture. That is, it has no dependence on transverse position. This does not hold when the azimuthal symmetry is broken.

For the fields obtained in simulation of the first zipper design, the effective voltage (including transit time effect) was calculated at various radii and azimuths over 45°. The results are plotted in Fig. 3. For a centered perfect square, there are no dipole or quadrupole components. There is, however, a slight octupole variation in the kick. Fitting the data to the function

$$G(r,\phi) = G_0\left(1 - \alpha r^4 \cos 4\phi\right) \tag{2}$$

yields a value of $\alpha = \sim 1.46\times10^{-5}\,\mathrm{mm}^{-4}$. Across a centered beam 100 microns wide, the fractional variation in acceleration would be only on the order of 1.5×10^{-9}.

HOM DAMPING AND TUNING

Higher-order cell modes excited by the beam should be well coupled into the side waveguide through the missing cell wall. This is like an extreme case of the damping manifolds included in NLC structures. Of course, the power could likewise couple back into the other cells. The overall mode structure of a zipper structure needs to be explored.

To dissipate higher-frequency power, the shorted ends of the side waveguides (opposite the coupling ends) could be extended in narrower waveguides, cutoff to the operating frequency and loaded with absorber. If necessary, a second set of stubs, opposite and offset from the first, could be added to each side waveguide. These would contain absorbers and have smaller narrow dimension. The accelerating mode would be prevented by symmetry from coupling to these, but they would serve also to damp all other longitudinal modes in the passband.

If cell tuning is needed to flatten the field profile in conjunction with a bead-pull, dimpling pins can be included in the two exposed walls of the cells. For phase adjustment, tuning pins can also be added between cells in the side waveguide.

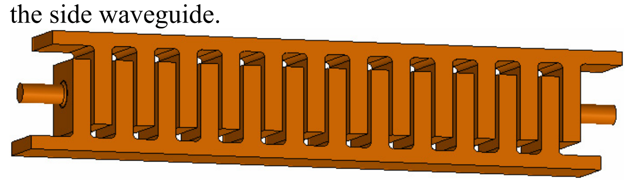

Figure 4: Example of a 24 cell, 15.75 cm zipper structure.

CONCLUSION

This novel structure geometry has attractive features, such as good efficiency, easy fabrication and damping, no coupling cell and a built-in circulator. It has been likened to an inter-digital slow-wave structure, and a similar idea for an interwoven SCRF accelerator, of more complicated construction, was presented in [2]. More study and design is needed to develop a complete, optimized zipper structure. Fig. 4 gives an indication of how it might look.

REFERENCES

[1] Alexej Grudiev, "Update on structure optimization procedure, input and results. CLIC reference structure," CLIC-ACE meeting, Jan. 16, 2008.

[2] P. Avrakhov, *et al.*, "Superconducting Accelerating Structure with Gradient as 2 Times Higher as TESLA Structure," presented at LINAC 04, Lubeck, Germany, Aug. 16-20, 2004.