TRANSVERSE INSTABILITIES IN A RELATIVISTIC KLYSTRON TWO-BEAM ACCELERATOR†

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Abstract

Transverse beam instabilities have been observed in the traveling-wave output structures of high-power microwave generators driven by induction accelerators. The relativistic klystron two-beam accelerator concept involves the transport of kiloamperes of current through many microwave output sections. Energy in both the cumulative and regenerative beam breakup modes could grow in these two-beam accelerator systems to levels that beam loss would occur. For induction accelerators the current term can be several orders of magnitude larger than values common for rf accelerators, presenting a difficult challenge for beam stability. In this paper we present experimental evidence of beam breakup in the output section of a high-power microwave generator, methods used to suppress the higher order modes in the power extraction sections, and computer modeling for transverse instabilities in larger relativistic klystron two-beam accelerator systems.

Introduction

The relativistic klystron two-beam accelerator (RK-TBA) concept[1] involves the transport of high current beams through many small resonant output structures. The electromagnetic wake from the passage of the drive beam will excite the higher order modes (HOM) of these output structures. Unless care is taken in the design and operation of the RK-TBA the HOM fields will build up to a level where the drive beam will be swept into the walls, resulting in rf pulse shortening. Within each of the output structures being studied for a RK-TBA, the regenerative beam breakup (BBU) is the principal BBU mechanism. However, for longer RK-TBA systems the cumulative BBU must also be addressed.

We have experimentally[2] demonstrated that good quality rf power can be produced using traveling-wave structures (TWS), but we have already seen problems with rf pulse shortening from beam induced higher order modes. Future higher rf power demonstrations will use higher beam currents, and the design of the output structures with regard to BBU will be even more critical. To increase the conversion efficiency of beam power into rf power we will also use additional output sections, increasing the probability of cumulative BBU. Long systems will require several mechanisms to weaken the BBU instability including phase mix damping.

TWSs are being investigated for use in SLAC's XL4 and VLEEP's klystrons using longer pulse lengths (~1 μs). The use of TWSs in these longer pulse regimes may require similar methods of damping the HOMs to elevate the BBU current threshold values to avoid rf pulse shortening and associated instabilities. TWS have also been applied to electron storage rings which have both high average current and long storage times. TWS allow additional control in these systems not available with standing-wave cavities[3].

Choppertron's Experimental Results

The design and construction of the choppertron is described in detail elsewhere[4,5,6]. The first part of the choppertron is a 5.7-GHz chopping system designed to produce a train of short beam pulses with a period corresponding to 11.4 GHz from the initial uniform beam. The chopper design has reduced sensitivity to the induction beam-energy sweep. Emittance growth is reduced by matching the axial magnetic field in the drift section to the beam

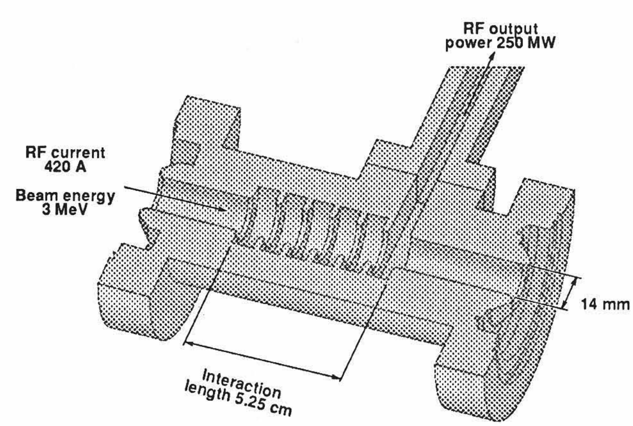

Figure 1. Schematic of TW1 Struture. (Printed with permission of Haimson Research Corp.)

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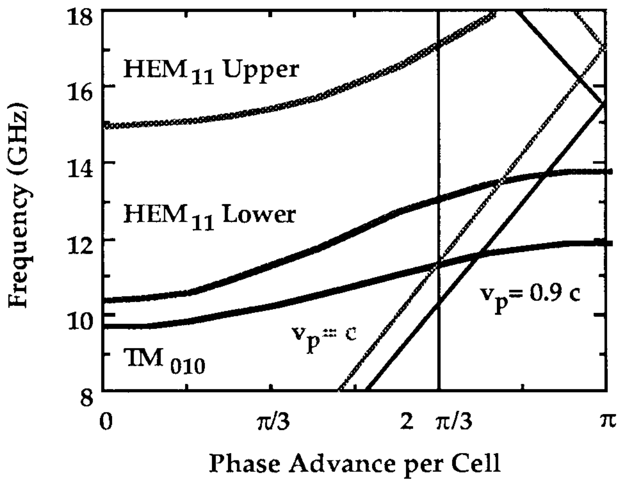

Figure 2. Dispersion graph of TW1 "extended"

TABLE 1
Parameters for the RF Output Structures

Design Parameter	TW1 & TW2	TW3
Fund. Resonant Freq.	11.424 GHz	11.424 GHz
Fund. For. Traveling Mode	TM_{010}	TM_{010}
# of Active Cavities	6	4
Phase Shift per Cavity	120°	120°
Aperture Diameter	14 mm	13 mm
Fund. Fill Time	1.05 nsec	1.35 nsec
Est. Q for first two cells*	1200	10
Est. R/Q for BBU mode	110 Ω	110 Ω
Output Power Achieved	250 MW	120 MW

*of the BBU mode

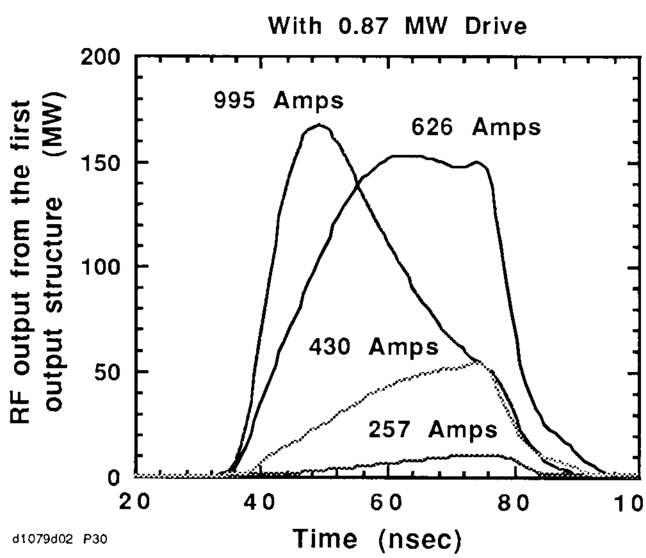

Figure 3. RF output for different input current. The current through the TWS is ~1/2 of input.

emittance and betatron resonance. The dc current is reduced by about half when the beam is fully modulated.

The last section of the original choppertron configuration consisted of two 11.4-GHz traveling-wave output structures. The use of high group velocity structures with short interaction regions provides a broadband, phase and temperature insensitive circuit. Two different types of traveling wave structures have been studied. Design parameters of these structures are given in Table 1. The identical TW1 and TW2 structures comprised the original output section of the choppertron. Figure 1 is a schematic of the TW1 structure. Figure 2 is the dispersion diagram for the TW1 "extended" structure (calculated with URMEL

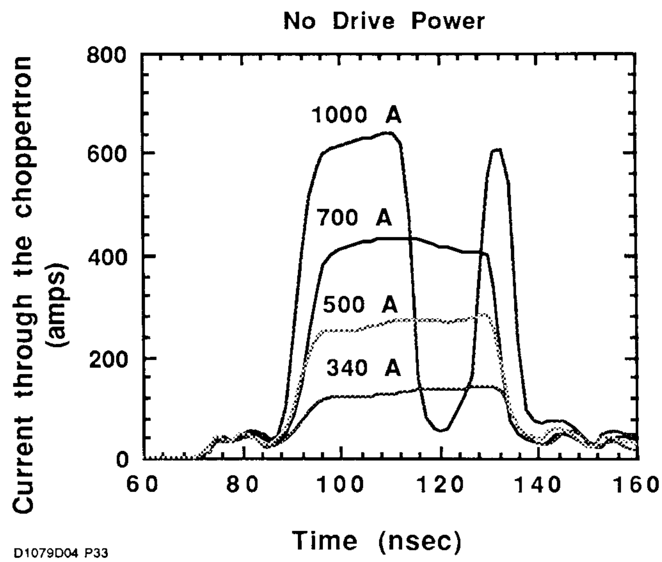

Figure 4. Through current for different input currents.

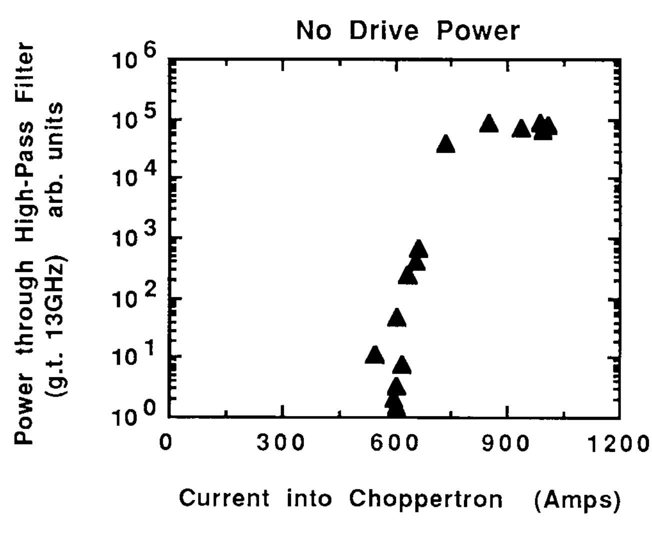

Figure 5. RF power in the 13.2 to 14.7 GHz band.

for an infinitely repeating cell structure). The actual TW1 structure consists of only six cells and has discrete resonances. Several of these resonances which interact strongly with the beam were measured[7] when the choppertron was tested.

Experiments demonstrated high rf output powers with the TW1 and TW2 structures, but with narrow pulse widths. The maximum total output power was about 420 MW with about 980 A of input current and 0.9 MW of drive power. The current pulse out of the choppertron was also narrow for this case indicating beam-wall intercept. For input currents below 600 A, the choppertron rf output was well modeled by computer codes. Figures 3-5 show scans where the beam transport before the choppertron was changed to vary the input current. Figure 3 shows the rf power for several input currents. Figure 4 shows the current pulse transported through the choppertron for different input currents (without drive power applied to the choppertron's modulator section). For input currents above 600 A the through current pulses generally had a sharp notch after ~20 nsec (see the 1000 A curve in Figure 4). Below about 600 A of input current, the rf output power would increase proportionally with the square of the input current.

The narrowing behavior of the through current and rf power output pulses is believed to be caused by the growth of transverse electrical fields in the output structures. The dispersion curves (see Figure 2) for the output structures show that the lower branch of the HEM_{11} mode crosses the speed of light line at approximately 13.6 GHz. By placing high pass filters in the rf output line we were able to measure the power in the 13.2-14.7 GHz band (shown in Figure 5). The power in this band had a sharp rise for current above ~600 amps. During later experiments, heterodyne measurements showed the BBU frequency to be at 13.6 GHz. The saturation in power shown in Figure 5 was believed to result when the electrons were driven into the walls. The short fill time of the structure might explain the recovery of the beam current in the second part of the current pulse shown in the 1000 A case in Figure 4.

Damped Output Structure

A third TWS (TW3) was designed with a broadband HOM de-Q-ing circuit for damping the HEM_{11}-like transverse modes[4] and was constructed by the Haimson Research Corporation. The de-Q-ing circuit consists of two slots in each of the first two cells of the TWS. The slots magnetically couple to both orientations of the dipole modes in each of the first two cells. The extracted power is absorbed into external loads attached directly to the outside of the cell. This design facilitates the use of these structures in the small bore solenoids that typically surround the TWS.

With the new TW3 replacing TW1, the choppertron produced stable, wide rf pulses, but the maximum output power achieved with 1000 A input current and full modulator drive power was only about 120 MW from TW3. The significant overlap of the lower HEM_{11} branch with the TM_{01}, see Figure 2, indicates heavy damping of the dipole mode will lower the Q for the fundamental monopole mode. The bottom portion of the HEM_{11} branch is lower than the fundamental extraction frequency (11.424 GHz). Since the field levels in the first two cells for the fundamental monopole mode are low, only a modest amount of fundamental power is absorbed by the de-Q-ing circuit. It was also especially important to damp the dipole mode oriented in the plane 90° from the main extraction port since this orientation previously had the higher Q. Transmitted currents up to 800 amps without transverse beam instability (compared to a threshold current of about 400 A for the original experiment with undamped structures) were achieved. This configuration produced a much richer spectrum of resonances[7]. However, only one resonance contributed significantly to the instability and it was associated with the undamped second structure.

Pulse Length Considerations

As can be seen in Figure 5 there is a current threshold level for the onset of the instability to have an effect for the choppertron within the 40-nsec beam pulse. Both experiments and simulations show a rapid exponential dependence of the HOM power with drive current. Once the mode is excited it has an explosive nature. The slope of the decay in output current in Figure 4 indicates that once the instability starts the beam current is lost within about 5 nsec. For design input beam conditions, if the rf power in the BBU mode reaches about 1% that of the fundamental extraction mode the transverse momentum "kick" given to the particles will be enough to drive the beam into the walls. Simulations[8] indicate that the current threshold is about 230 amperes for TW1 driven by a long electron pulse (~µsec) which enters the structure with a 0.1 mm offset from the z axis. Peak power operation of the choppertron was with currents over 4 times higher than this long pulse threshold value. The LLNL experiments have been with short rf pulses (40 nsec). For application to a collider at this frequency we will need to work with pulse lengths of 100-200 nsec.

Figure 6 show the effect of the pulse length on the threshold current in the computer simulations. This case is for single output structure of the TW1 type. The electron drive beam is at 2.5 MeV. The beam is entering the structure parallel to the TWS's axis and with an offset from the axis of 0.1 mm. The beam's initial radius is 4 mm. The structure is immersed in a 2 kilogauss magnetic field along the axis. The threshold current is determined when the beam's outer radius begins to hit the wall at 7 mm. The dipole mode being studied has a frequency of 13.6 GHz and is "lower HEM_{11}" like with a phase velocity near the speed of light and a group velocity approximately equal to 0.12 c.

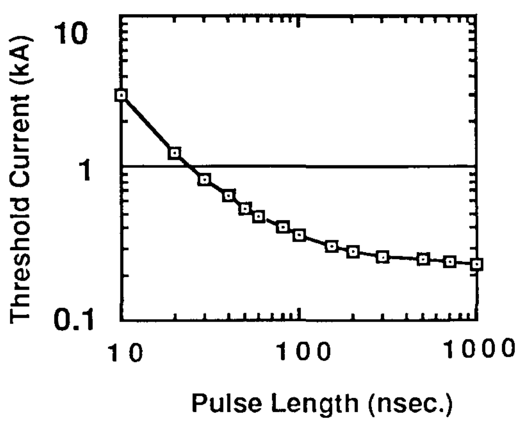

Figure 6. Threshold current verse time.

The decrease in threshold current in Figure 6 is relatively flat once the HOM power loss becomes comparable to the HOM power induced by the beam. The threshold current for a single structure (regenerative BBU) has a Q/R dependence[8].

The TWSs to be used in other klystrons are typically run at lower beam voltages with about 400 amps. These systems typically allow for more precise alignment of the electron beam with the TWS axis increasing the current levels achievable without beam-wall interception. Also the rapid change in electron's velocity in the output structures and the large relative instantaneous electron energy spread will typically increase the BBU current threshold.

Multi-output RK-TBAs

The choppertron had trouble with BBU only when running with two output structures. The drift tube connecting the TWS in the experiments to date has had a radius small enough to reduce the rf coupling between the TWS for the lower HEM_{11} branch. The threshold current for transverse excitation is drastically reduced if the rf power of a transverse mode is coupled between structures with similar geometries.

A new structure is being built with HOM power extraction loads in a drift tube section. This allows the use of a larger tube radius to ease beam transport issues. Damping in non-active sections is extensively used in many klystron and TWT amplifiers. In a RK-TBA the induction cells can also be used to reduce the coupling between rf output sections.

The use of additional output structures in a RK-TBA will increase the problem with cumulative BBU. For a long uniform system with cumulative BBU the transverse beam motion grows exponentially with a scale length L_{BBU}. The beam entering a latter TWS of the RK-TBA will have a larger transverse beam motion at its characteristic frequency. This motion will drive the regenerative BBU within this TWS.

The following illustration is given to demonstrate the importance of damping the HOM in the TWS and emphasizes the importance of other damping mechanisms in a long RK-TBA system. Figure 7 shows a simulation using TWSs that are closely packed with a fixed beam voltage of 2.5 MeV (no energy spread). The TWS are spaced at 11.2 cm intervals and the magnetic field is 2 kilogauss. The beam's initial radius is 4 mm. The threshold current is determined when the beam radius becomes larger than the drift tube's inner radius (7 mm) after 40 nsecs. The structures are the types shown in Table 1.

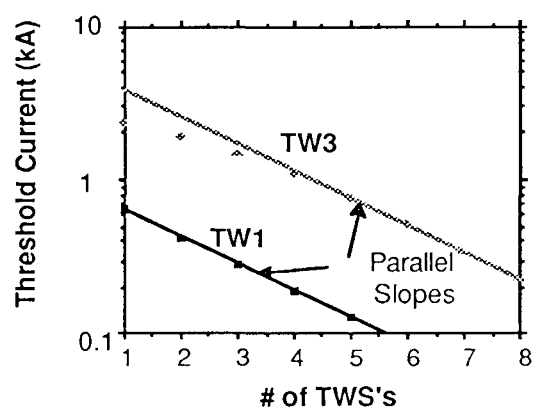

Figure 7. The beam current which can be used before the beam hits the wall for a given number of structures.

For a given magnetic focusing field the steady state cumulative BBU growth rate[9] is independent of the beam voltage in machines where the betatron wavelength is much smaller than the system. For a given growth rate and beam current the number of sections which could be used will be proportional to the magnetic field.

Staggered Detuning

Staggered detuning of the HOM frequencies is being actively pursued for the main accelerator structures being considered for linear colliders. This is accomplished by the use of cells with different geometry but with the same rf properties for the fundamental accelerating mode. Detuning requires that the frequency shift between non interacting sections, δf, be large compared to $f/(2Q)$. The Qs of the HOM for the TWS being considered for RK-TBA are relatively low and require that $\delta f \approx 1$ GHz. There are only about three usable geometries for the structures where the HOM response of one type of structures is shifted enough to move it's response out of the range of the response of the other types of structures. Still this should allow about three times the total number of TWS in an overall system using detuning than in a system in which all the structures have the same geometry.

Phase Mixed Damping

It was recognized early[1] that phase mixed damping from an instantaneous energy spread in the electron beam would be essential in a long RK-TBA to limit the growth rate of BBU. The TWSs now being consider have a higher shunt impedance that the standing-wave cavities original considered for RK-TBA designs. Code work is being pursued to develop a consistent design for a RK-TBA with realistic output structures[8]. We will also investigate the design of TWS which have lower Qs for the HOMs. If additional damping is needed in a long system we will investigate BNS damping (introducing a head-to-tail energy spread within the electron pulse).

Let k_β be the betatron wave number, γ the relativistic factor, ω_0 the BBU frequency, $Z_\perp$ the shunt impedance of a structure, L_g the average spacing between structures, and I_b the beam current. If there is a spread in k_β^2 values, δk_β^2, such that

$$\delta k_\beta^2\, \gamma > \pi \left[\frac{I_b}{17\ \text{kA}} \right] \left(\frac{\omega_0 Z_\perp}{L_g} \right)$$

then there will be no growth in transverse beam position[10]. For solenoid transport, k_β is inversely proportional to the particle energy and, therefore, a spread in k_β occurs if there is a spread, $\delta\gamma$, in γ. In the RK-TBA the value of $\delta\gamma/\gamma$ is typically large from the fundamental interaction of the structures during different parts of the fundamental rf period. Preliminary simulation with an energy spread during the fundamental rf period have shown a lower cumulative growth rate than simulation for a constant energy.

Conclusion

We believe that the BBU instability is now the most serious issue that needs to be addressed to reach a workable RK-TBA system design. This transverse instability arises from the interaction of the beam with the output structures now being consider for the RK-TBA. Work has started on finding a consistent design with realistic components. Aggressive damping of the higher order modes in the output structures appears to be necessary, but the RK-TBA design will need to include other damping mechanism to suppress the instability for a long RK-TBA system.

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