

# BRIDGING THE GAP BETWEEN CONVENTIONAL RF ACCELERATION AND LASER DRIVEN ACCELERATION\*

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## Abstract

For decades conventional RF accelerators have been built and operated with ever increasing capability thru a few tens of gigahertz in frequency. More recent research takes advantage of the continuing development of high peak power short pulse lasers to drive accelerator structures at optical frequencies. This jump from RF to optical frequencies skips four orders of magnitude in wavelength. With recent experiments that demonstrate high gradients in metallic structures at millimeter wavelengths one is compelled to consider the viability of new approaches for acceleration in the millimeter-wave to terahertz regime. This paper will explore some of these possibilities.

## INTRODUCTION

The traditional approach to linear collider design involves a series of choices aimed at producing an average beam power of about 10 MW. The basic choices are operating frequency and normal or superconducting structures. Normal conducting X-band structures are chosen in the hope of achieving high gradient operation and superconducting structures are selected in search of a reliable high efficiency system. Next comes the decision on power source options, which can be klystrons, with or without pulse compression systems, or two beam systems with klystrons used to produce the drive beam. Finally the modulator system is selected. For normal conducting accelerators this is usually a very high voltage modulator with its very inefficient pulse compression system, or a long pulse modulator for superconducting or two beam colliders. The end result is an overall system that is very expensive, inefficient, and not well suited to future expansion.

A multi-faceted approach is being explored for enabling an efficient, cost-effective design. This integrated approach tries to optimize the entire accelerator system that includes the accelerator structure, the RF source, and the modulator. This is accomplished by building on a basic physics understanding of high-gradient phenomenon in normal conducting structures, developing efficient novel structure designs that can be normal or superconducting, transformational RF sources based on low voltage operation, and intelligent modulators with feedback loops to recover energy from both the RF source and the accelerator structures. Finally, we are expanding our frequency range under investigation

to the millimeter-wave to terahertz region (100 GHz to 1 THz) because of its potential for extremely high gradients that makes operation at these frequencies worthy of consideration.

The following discussion is focused on the high frequency operation aspect, additionally motivated by the fact that accelerator developers have largely ignored this spectral region. This is partly due to the fact that powerful RF sources are not available at these frequencies with which to power accelerators. While RF accelerator technology has been developed as high as X-band with some experimental devices up to 17 GHz, the remainder of the RF spectrum has been skipped over in favour of laser-driven accelerators four orders of magnitude higher in frequency. The availability of high power lasers developed for commercial applications has made laser-driven acceleration a very active research area.

## MILLIMETER-WAVE STRUCTURES

A recent preliminary experiment was conducted using the SLAC FACET Facility's 20 GeV electron beam as the driver to excite a millimeter-wave structure and examine the RF breakdown characteristics. The traveling wave structure consisted of two copper slabs with a machined slow-wave structure as shown in Fig. 1.

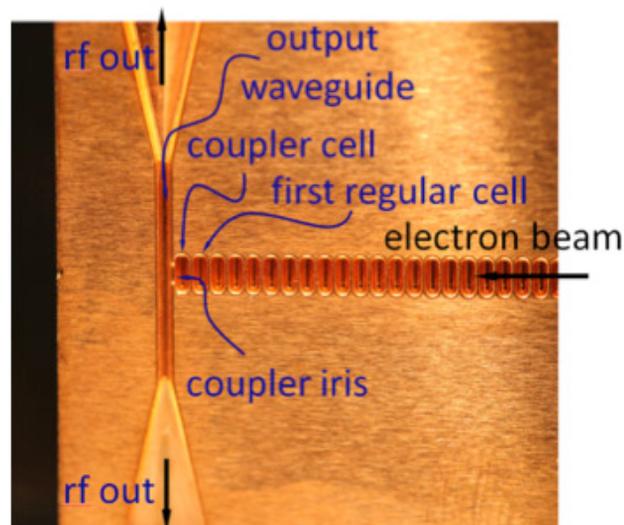


Figure 1: W-band 116 GHz traveling wave structure. Two such slabs are used on either side of the drive beam.

The structure consists of 112 cells. In the experiment the two slabs are placed on either side of the drive beam. The beam transfers RF energy to the structure as it passes through and the wave grows as it travels down the structure. Both the spacing between the slabs and the

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position of the drive beam between the slabs is adjusted as the coupled RF energy is measured.

After the structures were removed from the beamline they were examined in detail for evidence of breakdown. The autopsy showed evidence of breakdown in the structure as indicated in Fig. 2.

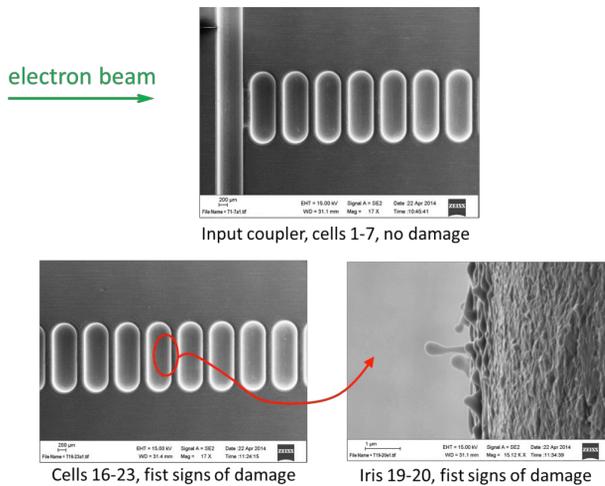


Figure 2: RF breakdown observed in downstream cells of the 116 GHz slow-wave-structure.

Measurements and calculations indicate that the structure surface was subjected to electric fields as high as 11 GV/m, which corresponds to an accelerating gradient of 5.5 GV/m. Although this work is just beginning and these results are very preliminary the indication is that gradients on the order of several GV/m are achievable at 116 GHz and perhaps even higher at 1 THz. An accelerating structure operating at these high frequencies and short pulses (a few ns) experiences relatively low pulse heating and hence the limits imposed on the breakdown rates due to surface fatigue [1-2] are no longer valid. The potential for high gradient operation will be limited by the value of the surface electric field. In this situation the only way to recover the luminosity with such a structure is to operate at very high repetition rate.

This experiment demonstrates the feasibility of continuing to research the potential of ultra-high frequency accelerator structures operating at low currents with short pulses and high repetition rate. However using a 2 km 20 GeV linac to power such a structure is completely unrealistic. What is required is a highly efficient THz source to power this class of accelerator structure.

### HIGH POWER TERAHERTZ SOURCES

The need for efficient, high power Terahertz sources to power advanced RF structures has forced new approaches. The approach commonly used to generate power at higher frequencies is to scale devices that work successfully at lower frequencies. This has been done pretty successfully with devices such as traveling wave tubes (TWTs) and klystrons to 10s of GHz. The physical

dimensions of fundamental mode linear-beam devices such as these scale as the frequency<sup>-2</sup> so a device at 100 GHz is 1/100<sup>th</sup> the size of a similar device operating at 10 GHz. The shrinking size means that RF power *density* and electron beam *density* in the structure correspondingly rise if one attempts to maintain the same output power level. This proves to be impossible and inevitably the output power level must drop for the device to work reliably. This is what leads to the typically rapid falloff in power with frequency.

Researchers are attempting to push TWT technology to 220 GHz with an expected output power goal of 50 watts [3]. The beam tunnel in the device through which the beam must propagate is tiny, 100-200 μm, making the device very susceptible to beam interception and subsequent heating. Scaling this to 1 THz would significantly reduce the size even further. The need for efficient, high power Terahertz sources to power advanced RF structures calls for new approaches.

We have developed a new approach for THz generation that uses a large, overmoded interaction structure with dimensions on the order of centimeters versus the 100-micron size of scaled conventional linear beam devices. Our THz amplifier concept, inspired by coherent synchrotron radiation (CSR) instabilities in storage rings and negative mass instability induced beam bunching, can be considered a variant of the High-Harmonic large-orbit Cyclotron-resonance Maser (HHCM). It comprises a beam interacting with the electromagnetic field propagating in a curved metallic shell segment that is open (no metallic boundary) on the inside. Such a structure can guide a spherical wave mode, as the fundamental operating mode, where the dimensions of the shell are much greater than the operating wavelength (about 0.3 mm @ 1THz). A conceptual drawing of the interaction structure for our variant of the HHCM is shown in Fig. 3. The feature sizes depend on the frequency, beam energy, and harmonic number that are chosen but would be substantially larger than the operational wavelength for typical parameters.

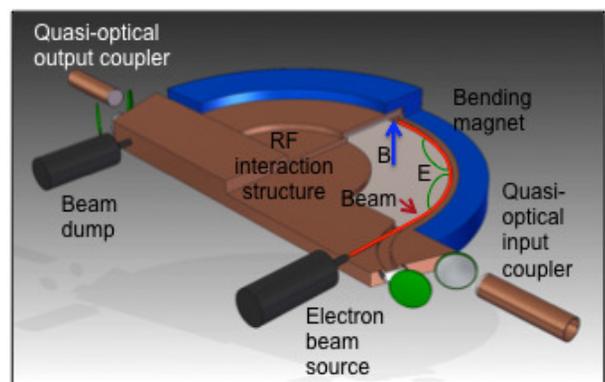


Figure 3: Conceptual layout for the high-harmonic large-orbit cyclotron maser.

For example a fundamental mode resonator at 1 THz could be constructed with a 0.5 m radius and 3 cm extent in the z direction (perpendicular to the beam direction).

Interaction with that mode would be over a very large number of wavelengths. These types of fields are commonly referred to as “whispering gallery” electromagnetic waves. A robust design requires a very careful consideration of the beam optics and dynamics in the system.

Tailoring the polar extent of the metallic shell to that required to support the desired mode will result in a structure where competing modes with a lower resonant frequency will simply leak out and not result in a growing electromagnetic mode. Higher order modes will be supported by the structure and could potentially couple to the beam. However, in the same way that a single mode interaction can be obtained in a highly overmoded gyrotron cavity, mode discrimination can be achieved by proper spatial positioning of the electron beam and matching of beam and RF phase velocity. Furthermore, an electron beam with the appropriate energy and guiding (bending) magnetic field could be made to have the same cyclotron frequency as the rotating electromagnetic (EM) wave guided by the shell. The magnetic field required is quite modest: for a 100 kV electron beam the required magnetic field is only 220 gauss. The beam interaction with the EM wave is similar to that associated with cyclotron resonance masers or coherent synchrotron radiation (negative mass instability). In this type of interaction, electrons traveling on a circular path that gain energy due to interaction with the EM wave move to a longer path than those that lose energy. Hence, higher energy electrons fall back and lower energy electrons move forward resulting in micro-bunching of the beam, which moves collectively with the same speed as the EM wave. Once bunched, the beam then can be made to give up its kinetic energy to the EM wave, resulting in its amplification.

Initial scoping studies and numerical calculations are underway examining the interaction between the beam and the electromagnetic wave and looking at gain, stability, and mode competition. Also dispersion engineering of the curved metallic shell is being studied to achieve the required phase velocity so the synchronous orbit of the beam can be put at the peak value of the electric field of the guided mode. Finally a design for quasi-optical input and output coupling to the structure is being developed to efficiently convert the whispering gallery spherical shell mode to a Gaussian beam.

In studying the various design configurations both high average power and high peak power regimes are being considered. Beam energies from 10s of keV to a few MeV are being studied. A high voltage beam is more suitable for generating high peak power and could be supplied by an advanced highly efficient, compact linac driver that is also in development. A compact, high average power source in the 1-10 kW range would be based on a more conventional electron gun.

## CONCLUSIONS

A non-traditional approach is being developed to significantly increase the efficiency and decrease the cost

of high-energy accelerators. This approach utilizes advances in our understanding of high gradient structure performance and explores the possibility of operation in the 100 GHz to 1 THz spectral region which has up to now been largely ignored due to the lack of available high power sources. Initial experimental and numerical studies indicate promising concepts for both accelerator structures and the power sources to drive structures at these frequencies.

## ACKNOWLEDGMENT

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