Design calculations for high-space-charge beam-to-RF conversion

Phase I SBIR

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Final Report

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Table of Contents

Executive Summary

Accelerator facility upgrades, new accelerator applications, and future design efforts are leading to novel klystron and IOT device concepts, including multiple beam, high-order mode operation, and new geometry configurations of old concepts. At the same time, a new simulation capability, based upon finite-difference “cut-cell” boundaries, has emerged and is transforming the existing modeling and design capability with unparalleled realism, greater flexibility, and improved accuracy. This same new technology can also be brought to bear on a difficult-to-study aspect of the energy recovery linac (ERL), namely the accurate modeling of the exit beam, and design of the beam dump for optimum energy efficiency.

We have developed new capability for design calculations and modeling of a broad class of devices which convert bunched beam kinetic energy to RF energy, including RF sources, as for example, klystrons, gyro-klystrons, IOT's, TWT’s, and other devices in which space-charge effects are important. Recent advances in geometry representation[i] now permits very accurate representation of the curved metallic surfaces common to RF sources, resulting in unprecedented simulation accuracy. This new technological development is expected to transform the design process for a wide class of beam and RF devices, and at the same time provide an unprecedented level of precision.

In the Phase I work, we evaluated and demonstrated the capabilities of the new geometry representation technology as applied to modeling and design of output cavity components of klystron, IOT's, and energy recovery srf cavities. We identified and prioritized which aspects of the design study process to pursue and improve in Phase II.

The development and use of the new accurate geometry modeling technology on RF sources for DOE accelerators will help spark a new generational modeling and design capability, free from many of the constraints and inaccuracy associated with the previous generation of “stair-step” geometry modeling tools. This new capability is ultimately expected to impact all fields with high power RF sources, including DOE fusion research, communications, radar and other defense applications.

The VORPAL code is licensed freely to our collaborators at the DOE laboratories, and so the new modeling RF capability will be available to DOE funded fusion researchers, projects and programs. The new capability will also have application to numerous research and design issues with similar multi-cavity beam-to-RF conversion physics. One immediate topic of interest is energy recovery in the next generation of high current linacs. It is expected that the technology will be of great interest to commercial manufacturers of these RF sources, and hence this provides a clear commercial marketplace for products based upon this technology. Tech-X

Corporation already markets VORPAL-derived software as a commercial product. Hence this new technology also has a clear commercialization path.

Comparison of actual accomplishments with goals and objectives of the project

The Phase I emphasis was primarily on development and demonstration of the new geometry representation technology as applied to the modeling of output cavity components of klystron and IOT devices, and other beam-to-RF conversion structures, including energy recovery srf cavities of Linacs. In all of these components the beam undergoes significant average deceleration as it drives the RF cavity mode, thus resulting in enhanced space-charge density and resultant space-charge forces, and the goal was to demonstrate self-consistent modeling of the simultaneous action of the mode field and the space-charge field.

The Phase I has demonstrated that the new "cut-cell" geometry modeling provides exceptional modeling capability, both in terms of device detail, and in terms of numerical accuracy. It was found that particle simulation will involve some challenge in the energy recovery simulation, primarily resulting from the need to control particle noise levels. Additional capability which could aid in the design simulations have also been identified.

Finally, a number of issues were identified in Phase I which, although not crucial to the overall feasibility of the simulations, nevertheless adds difficulty to the process. Some of these areas include: a) the need for voltage-feedback mechanism to the existing voltage boundary, b) more general translation capabilities for data from non-VORPAL field solvers, in particular for the magnetic field, c) partial transparency of screen objects, and d) better particle statistics diagnostics.

Per-Task Accomplishments

(Note, this section was added after the original final report was written.) The following provides a succinct discussion of the accomplishments vis-à-vis the proposed task.

Task 1. Tools for Simulation of Output Cavities

Proposed: **Tech-X will construct VORPAL input files, with accurate curved-surface geometry representation, for design simulations of single and multiple cavity beam-to-RF conversion structures, and develop methods for their use.**

Accomplished: This task provided the "backbone" of the Phase I work, and the original objectives of this task were well met. The subsequent section of this report entitled "Cavity Simulation Demonstration" provides details. Input files, and reusable sections of input files, were written, and procedures on how to use the input files were developed. Successful simulation of remarkably accurate 3-D curved-surface geometry was accomplished. Simulations demonstrating the extraction of frequency spectra and mode patterns were accomplished, in multiple-cavity structures. Simulations demonstrating the evaluation of the R/Q (stored energy) of a cavity and the Q of a HOM coupler were accomplished. The techniques and input file sections developed in this task have become common practice, are now included in several regression tests and example files for the VORPAL software, which is a commercially licensed product.

Task 2. Benchmarking and Diagnsotics

Proposed: **Tech-X will perform benchmarking studies with the design input files, and will implement diagnostic capability to insure adequate and useful data for benchmark comparisons.**

Accomplished: There are two parts to this task, benchmarking, and diagnostic capability necessary to perform the benchmarking. In both areas, the original objectives of this task were met satisfactorily. Much of the diagnostic capability developed during the Phase I is incorporated into the input files and techniques, and also enabled the Task 1 activities. Benchmarking was primarily focused upon meeting the published results of the 9-cell Tesla cavity, and its notch-filter HOM coupler. The results of this benchmark were very favorable, and have ultimately helped provide credibility for the Vorpal software in other projects, such as the COMPASS SciDAC program. Good matches to published results for frequency spectra, and HOM Q-loading at specific frequencies were obtained essentially on 1^{st}-attempt basis, thus validating the cut-cell EM simulation techniques at the heart of this project. Additional benchmarking, on other devices would clearly have been very desirable during this project, but was not possible in the allotted time and budget. (NB, October 2008 – subsequently, similar benchmarking during the course of numerous other projects, involving both accelerator cavities and microwave sources, has been performed, and continues to yield very favorable results.)

This project developed and implemented, within the VORPAL software, diagnostics measuring integrated electric field (voltage), and poynting flux, which are necessary for benchmarking of the HOM Q-loading, and the stored energy parameter, R/Q. This project continued the development of post-processing capability for measuring amplitude of an oscillating signal, determining DC filtered (cycle-averaged) field quantities, including particle currents, and determining very small changes in frequency, using a filtered, zero-crossing algorithm. An important point is that these post-analysis capabilities are encoded in a simple point-and-click interface, called VorpalView, allowing instant analysis at the touch of a screen-button, e.g., with essentially no learning curve. This provides important commercial benefit and attractiveness. (NB – While useful, there are numerous additional diagnostic capabilities, such as spatial growth of RF amplitudes, average particle energy, and particle wall loading, which were not implemented due to time and budget constraints. The Phase II did not go forward, and so this important area of ready-to-run diagnostics remains one of the challenges for this software, in terms of commercial attractiveness.)

Finally, the level of interaction with researchers at JLab on this task was less than anticipated, due to the use of existing published data for benchmarking, rather than data supplied by the laboratory.

Task 3. ERL Beam to RF conversion feasibility

Proposed: **Tech-X will provide a feasibility evaluation for re-use of the design input files developed for beam-to-RF conversion in klystrons and IOT's in the problem of estimating the conversion efficiency in energy recovery Linacs.**

Accomplished:

This task was accomplished, but with the evaluation being that feasibility issues remained and needed to addressed in the Phase II. The result of the feasibility evaluation determined that there were practical difficulties in the energy recovery simulations relating to particle noise and numerical Cerenkov emission. These difficulties were due to the generally higher level of energy, in particular the larger relativistic speeds of the beam entering the energy recovery calculation, than what is commonly found in IOT's and klystrons, where this type of calculation is prevalent. These difficulties are illustrated in Figure 8 of this report. Algorithmic remedies for these difficulties were researched, and one in particular, based upon the so-called "perfect dispersion" technique, was proposed to be implemented in the Phase II effort. (NB – The Phase II did not go forward. Implementation of the "perfect-dispersion" algorithm within the

VORPAL software remains at a very primitive evaluative stage, not suitable for general use in complex problems.)

As expected, additional capabilities needed for advanced modeling of IOT's, klystrons, and energy recovering, such as an adjustable transparency screen model, improved importing of magnetic field data, etc., were also identified and delineated, with more details in the body of the report.

Task 4. Gun-to-collector simulation feasibility

Proposed: **We will construct input VORPAL input files illustrating the geometry representation capability of the software in terms of gun-to-collector full-device representation.**

Accomplished:

This task was only partially accomplished. Sophisticated input files with geometry representations using advanced macro-language and python-language functionality were created, however, these concentrated on cavity structures and couplers to the cavities. The full intention to create geometry of guns and collectors, in addition to the cavity simulations, was not fully met, due to time constraints, and redirection of effort in researching the feasibility issues which arose in the previous task. (NB - Nevertheless, the geometry representation techniques developed from these cavity simulations were very general in nature, and have permitted in the meantime, as part of a different proposal effort, easy representations of an IOT gun, as well as representations of magnetrons, torii for fusion devices, ECRIS vacuum vessels, psuedospark chambers, etc. E.g., the difficulty completing this task was one of available time, rather than software capability.)

Technical Background

Bunched beam devices in which space-charge forces are present can be difficult to model with cavity modal methods because of the difficulty in separation of the intra-bunch longitudinal space charge fields from the modal field, since both fields are effectively coherent in frequency and polarization. Analogously, the space-charge beam contributes a cavity loading, Q_{beam}, and frequency shift, df_{beam}, to the modes of a cavity, which must be estimated independently somehow, often in an approximate manner, and inserted into the modal evolution equations in a synthetic manner. Self-consistent methods based upon simultaneous particle-in-cell pushers and finite-difference Maxwell solvers provide the cure for this problem, but introduce new difficulties, because of the constraints of the finite-difference Maxwell solvers.

The Maxwell solvers reproduce the cavity mode oscillations in the specific geometry of the cavity or other power extraction structure, and hence their effectiveness is due in large part to the accuracy to which they represent that geometry. Until very recently, these Maxwell solvers have been constrained by their finite-difference grid, such that metallic walls, dielectric loadings, and other geometric detail was required to coincide with the grid lines. Or in the case of curved surfaces, or flat surfaces obliquely aligned to the grid, the surface was required to follow the grid along a "stair-stepped" shaped approximating the actual surface. This stair-stepping leads to an inherent, and practically random, error on the order of a single grid cell, for any linear dimension across the geometry. Since this error is essentially order $\delta x/Length$, it qualifies as first-order error, which is an onerous price to pay, but one which has never-the-less been worth paying, for the benefit of space-charge self-consistency.

The implications of this first order error for klystrons and other multiple cavity devices, is particularly severe, and hence the computational design of klystrons has necessitated remedial techniques for this problem. Typically the fundamental mode frequency of a klystron cavity is determined from the cavity radius, which is usually resolved by anywhere from 20 to 100 cells. If left to the vagaries of the first order error stair-stepping, this results in a random 1-5% error in cavity frequency. Yet, for accurate modeling of a klystron, the frequency must be precise to a level of at least $^1/_{10}\ Q_{cold}^{-1}$, where Q_{cold} is the cold (no-beam) loss-parameter for the cavity. Q_{cold}'s are typically of the order of 100 for output cavities in many klystrons. Hence, the first-order error results in frequency error 10 times the allowable, and hence remediation is necessary. In practice, one artificially adjusts the radial grid through trial and error, testing the resulting frequency after each adjustment, in order to achieve the exact frequency required. Once achieved, the grid must be emphatically fixed, in order to insure that the mode frequency doesn't change. This process is even more important when modeling intermediate cavities of a klystron, where Q's are on the order of 10^3. And by way of comparison, projected high current (and space charge) srf cavities for energy recovery Linacs will have Q's on the order of 10^4.

There remain three difficulties with the stair-stepping remediation procedure outlined above. First is that even though the fundamental frequency may be tuned exactly in this manner, all other modes may experience the characteristic 1st-order 1-5% inaccuracy. If accurate high order mode spectrum is important, then this becomes a nearly insurmountable problem. Second, if there is more than one cavity, with slightly different radius and/or frequency, which is a common design aspect of many klystrons and other devices, then it becomes impossible to adjust the grid to satisfy frequency requirements for both cavities simultaneously, and additional remediation techniques are required. Third, is that if one wishes to change grid resolution, or add geometry before or after the cavity that has its own radial grid constraints, e.g., the gun or collector, then one must redo the time-consuming frequency remediation task, once the new grid has been set.

Modeling with Cut-Cell Technology

We have taken advantage of the recent advances in geometry representation, which we refer to as the “cut-cell” methods, to develop state-of-the-art simulation techniques, and use these for design calculations of klystrons, or other RF sources, and Energy Recovering Linac beam-to-RF conversion, for DOE accelerator facilities. These advances are expected to allow finite-difference particle-in-cell modeling of an entire RF source, including such components as the gun and collector, which have traditionally been difficult or impossible to model with such tools.

The “cut-cell” technology, now established in the VORPAL software, provides near perfect representation of curved metallic walls, thus removing the 1st-order error in geometry and dimension. Figure 1 illustrates this breakthrough in geometry representation capability.

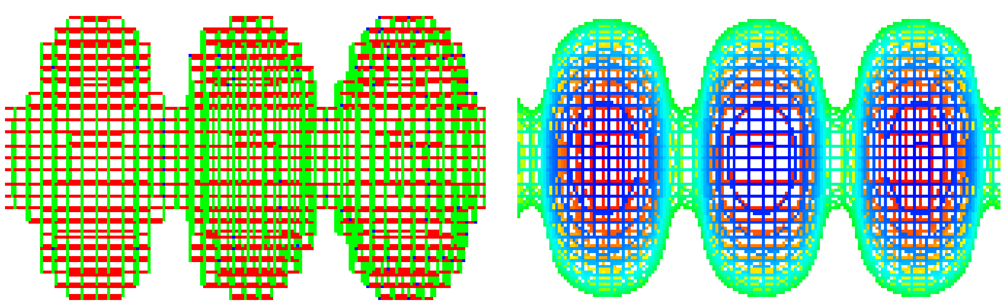


Figure 1. *Illustration of the new “cut-cell” capability in the VORPAL software to represent curved surfaces in finite difference simulations. Figure at left is traditional “stair-stepped” representation, and smooth figure at right is produced using the new capability, with identical grid spacing.*

In many situations, this new capability results in improved speed, by reducing the number of cells traditionally required to model certain common shapes. Figure 2 shows the impact of the new capability in the common situation of representing a cylindrical drift tube and cavity aperture. This situation typically requires extra small cells because of the need to faithfully represent the round cross-section in a "stair-stepped" manner. Now, perfectly round cross-section shape can be achieved with many fewer cells.

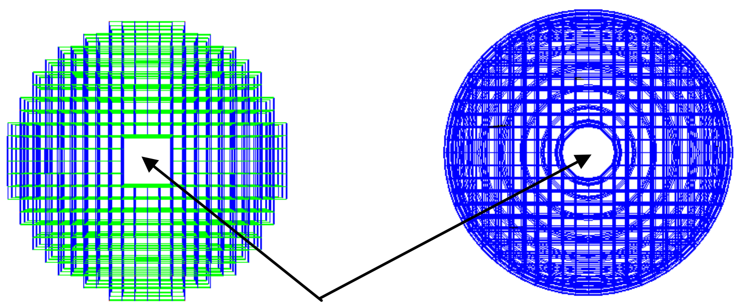


Figure 2. *End views of a cavity representation using stair-stepped boundaries (on the left) and cut-cell boundaries on the right. The VORPAL code uses cut-cell boundaries to get more accurate results, which is especially important in the drift-tube aperture region, as indicated with the arrows.*

Demonstration of present "cut-cell" algorithm in the VORPAL software[ii] is shown in Figure 3a). Red lines indicate the slopes associated with 1st and 2nd-order accuracy. The two data lines show the frequency error, as cell-size is decreased, when stair-stepped boundaries are used, and when partially-filled-cells (PFC) are used, for a circular (2-D) cavity. The stair-stepped boundary shows the characteristic 1st-order error slope. The PFC (partially filled cell) line shows considerable oscillation, but a general slope and upper-bound level of error consistent with 2nd-order accuracy, and similar to other published implementations of this algorithm. The source of oscillation is not fully known, but indicates that for certain cell sizes, unusually low error is possible. This data is from an implementation of the "Dey-Mittra" PFC algorithm which was recently implemented in the VORPAL software. This algorithm has provided a foundation for a more advanced algorithm, known as the uniformly-stable-conformal (USC) method. Figure 3b) illustrates the expected error from this more advanced cut-cell technique, as compared to stair-stepped and PFC boundaries[iii] (Figure adopted from Reference iii). The primary point to take from this data is that the cut cell methods provide for the possibility of 10^{-4} error, with grid cell resolution of existing simulations. With this capability, one has sufficient geometry resolution, and flexibility, that: 1) it is no longer necessary to perform the tedious frequency remediation tasks in the cavity design simulations, and 2) the higher-order mode spectrum is accurate to the same order as the fundamental frequency.

a) VORPAL **b) Reference iii**

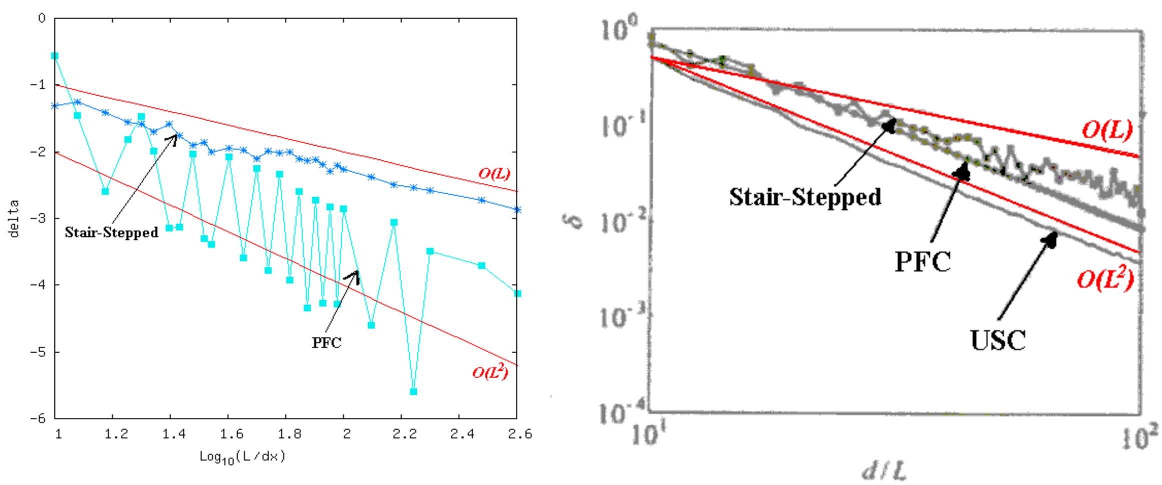
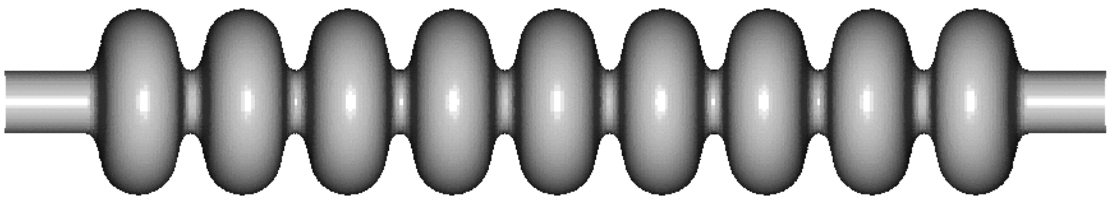


Figure 3. Frequency error scaling curves, showing 1st order error for stair-stepped boundaries and 2nd order error for cut-cell methods. *a) shows recent implementation of partially filled cells (PFC) in VORPAL, b) shows results adapted from Reference iii, including universally stable conformal (USC) 2nd-order method with smaller error.*

Use of simulation in design of klystrons and IOT's

We are focused on providing modeling capability of the output cavity structures, in klystrons, and possibly other devices, such as IOT's, since this is the primary test of accurate beam to RF conversion. We include in the demonstration the ability to model multiple-cavity structures. If the geometry of an output coupler, whether aperture to a waveguide, or coupling loop, is not too fine-detail, we believe that it is best to include the transition from cavity to output waveguide as an integral part of the simulation. This provides accurate $Q_{external}$, and proper frequency shift due to the coupler geometry. We have produced design quality simulations of these cavities, with a strong emphasis on accurate geometry representation.

Design calculations require a high degree of confidence in each component of the simulation, and independent verification runs, somewhat analogous to laboratory testing, are typically used to provide this level of confidence.[iv] Thus, one develops "cold-test" methods to test cavities and other electromagnetic circuit components for their circuit behavior in the absence of a beam. For example, in the case of output cavities, this would be the cavity frequency, R/Q, and cold-test Q. The 3-D simulations of output cavities include accurate geometry couplers, and thus, we can perform specific simulations to determine the circuit parameters of the coupler, for example, $Q_{external}$, S11, and any cavity frequency shift associated with the coupler geometry. Multiple cavity beam-to-RF conversion structures are also of great interest, and specific VORPAL input files and simulation methods have been developed to provide the additional circuit information needed for their design, for example mode spectra, traveling wave band edges, and group velocity estimates. Figure 4 shows such a simulation, known as an impulse response simulation, which rapidly provides the mode spectra for a multiple cavity structure.



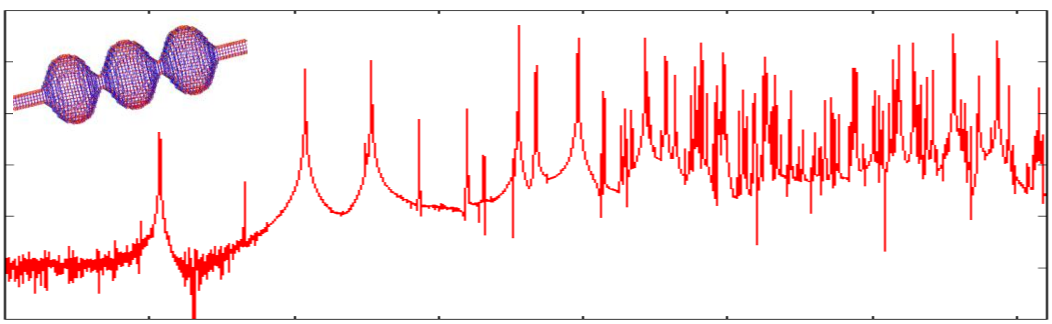


Figure 4. Upper) *VORPAL "cut-cell" geometry representation of a 9-cell TESLA srf cavity. The beam-to-RF conversion associated with Energy Recovering Linacs is similar to the beam-to-RF conversion processes of RF sources, particularly those with output cavities such as klystrons. Thus many of the same design tools for RF cavities can serve to estimate the recovery efficiency of an ERL. Lower) Impulse response mode spectrum from a VORPAL simulation of a 3-cell cavity.*

The "cut cell" capability also has potential application beyond cavities and other structures used for particle-to-RF conversion. For example, the RF sources often use electrostatic "depressed" collectors to electronically recover additional spent-beam energy. These structures often contain quite complex geometry, including conical shapes and surfaces at oblique angle to the beam axis. Modeling of these components is often done with finite-element electrostatic models, however time-domain electromagnetic modeling would be very beneficial, since the spent beam may still contain significant RF character, yet this has been difficult in the past, because of the poor "stair-stepped" geometry representations.

Another possible application of the cut-cell technology would be for modeling of the electron gun. This component typically contains spherical or conical shaped electrodes and emitting surfaces. And due to the high space-charge density (low-velocity) at the emission surface, the particle trajectories are very sensitive to the curved geometry of these electrodes. Hence "stair-stepped" geometry representation is wholly unsatisfactory for modeling this component, and again electrostatic finite-element software is typically used instead. Nevertheless, there may be reason to want to model this component with the new "cut-cell" technology, specifically: 1) certain RF sources, including IOT's, use grids near to the emitting surface to generate oscillating current and space charge in close proximity to the emission surface, such that electrostatic modeling of the gun is not entirely satisfactory, 2) even for static guns, such modeling would allow complete end-to-end modeling of the device from cathode to beam dump with the same modeling tool, without need to "match" data from electrostatic (gun), to electromagnetic (cavity), and back to electrostatic (collector), and 3) the time-domain modeling can sometimes provide a more self-consistent self-magnetic field. Usefulness of the cut-cell modeling technology for the gun component would be improved, if it could be demonstrated that accurate space-charge limiting currents from the cut-cell representation of spherical cathodes is possible.

Interaction with Researchers at National Accelerator Facilities

A key element of this project has been the collaboration with experimentalists at the Thomas Jefferson National Laboratory. Work on this project include visits to JLab by Tech-X personnel, Drs. David Smithe and Peter Stoltz.

A very effective use of computer simulation technology is a coupling of numerical specialists, e.g., Tech-X personnel, with laboratory experience. There are generally two reasons for this. First, the experimental expertise can help focus simulation problem definition in terms of real-world requirements and limitations. For example, while numerical specialists are concerned with insuring proper algorithmic scaling of error for smaller and smaller mesh, the reality is that for a fixed problem, it is often the absolute error that matters in the real world. Hence, the compromises that result from balancing available computing resources with experimentally required accuracy level, are an integral part of the simulation process.

Second, the simulation tool is essentially an electronic laboratory. In practice, laboratory techniques used to evaluate component performance often have simulation analogues. Thus the laboratory techniques themselves provide inspiration for useful numerical procedures. In addition, in sharing such techniques, it helps insure that numerical specialist and experimenter are communicating effectively, and providing benefit to each other.

Given the potential benefits for highly productive interaction between numerical specialist and experimenter, we feel that a structured approach to insuring this interaction is warranted.

Interaction with JLab personnel included discussion of possible use of this same design capability for determining the efficiency of the energy recovery process occurring in srf accelerator cavities of Energy Recovering Linacs (ERL's). There are many similarities between the beam-to-RF conversion processes which occur in a klystron output cavity or IOT, and the beam-to-RF conversion process which occurs in an ERL. In both cases a bunched beam gives up kinetic energy to a dominant cavity mode, and for design purposes, one is very concerned with getting an accurate prediction of how much power is thus transferred from beam to the cavity mode. This will become a more important issue for design of future ERL applications, where higher beam space charge and FEL action, for example, can lead to increases in beam spread, and hence reduction in energy recovery efficiency.

Summarize project activities

The Phase I has demonstrated that the new "cut-cell" geometry modeling provides exceptional modeling capability, both in terms of device detail, and in terms of numerical accuracy. It was found that particle simulation will involve some challenge in the energy recovery simulation, primarily resulting from the need to control particle noise levels. Additional capability which could aid in the design simulations have also been identified. Finally, a number of issues were identified in Phase I which, although not crucial to the overall feasibility of the simulations, nevertheless adds difficulty to the process.

Cavity Simulation Demonstration

Simulations looking at cavity frequencies of extant hardware have found essentially exact agreement with known experimental results, see Figure 5. The results of this figure were achieved essentially "on the first try", based upon specified blueprints, and did not require tuning of any sort.

Techniques have also been developed which permit excitation of single modes, specifically the fundamental acceleration / deceleration mode in multi-cell cavities. An example of such is shown below in Figure 6. For accuracy in the energy recovery calculation, a realistic pure-mode excitation is a necessity.

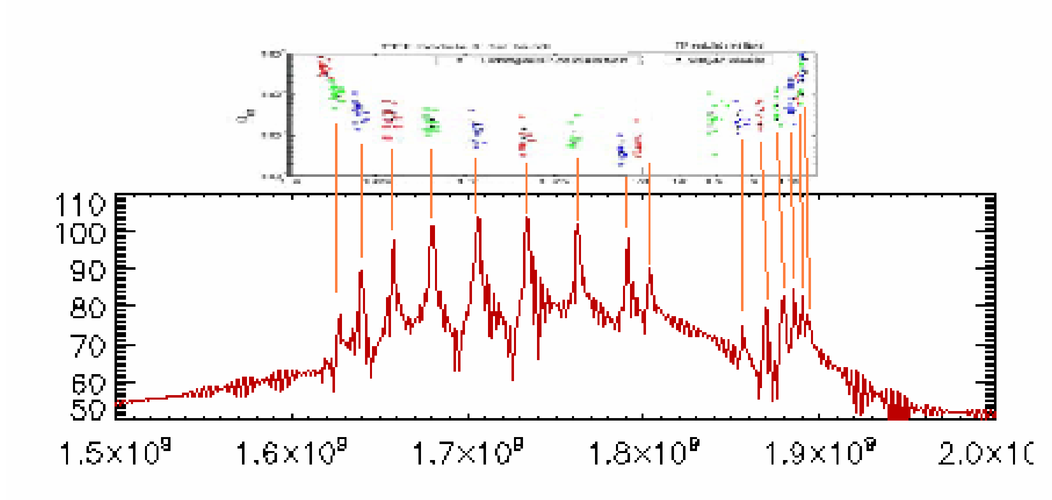


Figure 5. *Cavity mode structure (TE-HOM and TM-HOM) of 9 cell Tesla cavity. Top is experimental results, bottom is the spectrum from the simulation. These results are based solely on specified blueprint geometry, and did not require "tuning" of the cavity volume in any fashion.*

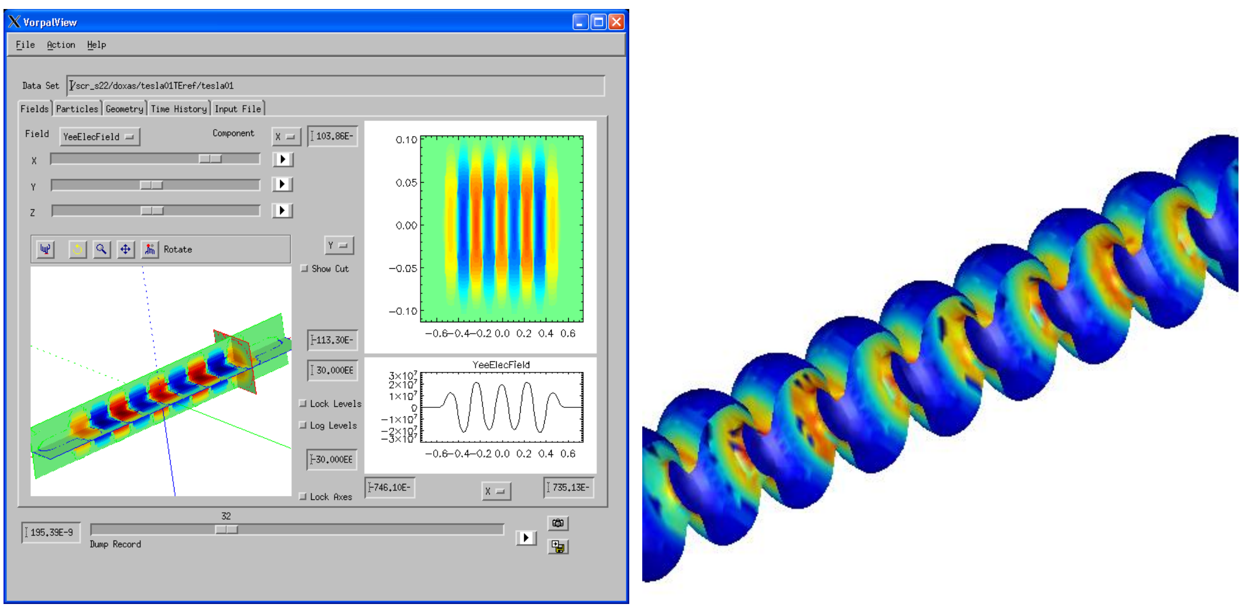


Figure 5. *Illustration of the fundamental acceleration / deceleration mode in a 9-cell Tesla-like cavity. The ability to set up these modes is critical to accurate energy recovery calculation.*

The new modeling capability has also been used to demonstrate remarkable detail for coupler structures, as illustrated by the formteil coupler geometry in Figure 7, such that one may now consider faithful representation of cavity output coupler structures.

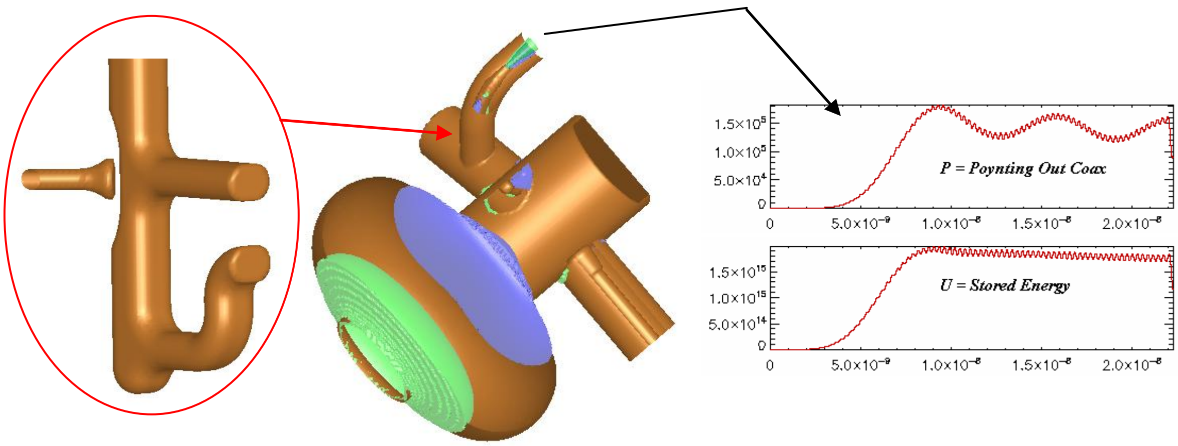


Figure 7. *Detail from a true-geometry simulation of a srf end-cavity with HOM and input couplers. Graphs show power out the coupler's coaxial line, and cavity stored energy. A significant advantage of being able to model the coupler directly is that the boundary conditions are applied to the waveguide or coax, where they are simplest.*

Identification of Simulation Challenges

The subject of particle noise and suppression of numerical Cerenkov emission, see Figure 8, and proper representation of wake fields continues to see improvements, and it is advisable to insure that the design studies incorporate the latest technology, or at least the optimum technology for this simulation regime. We have identified this as the most likely challenge to the energy recovery calculation.

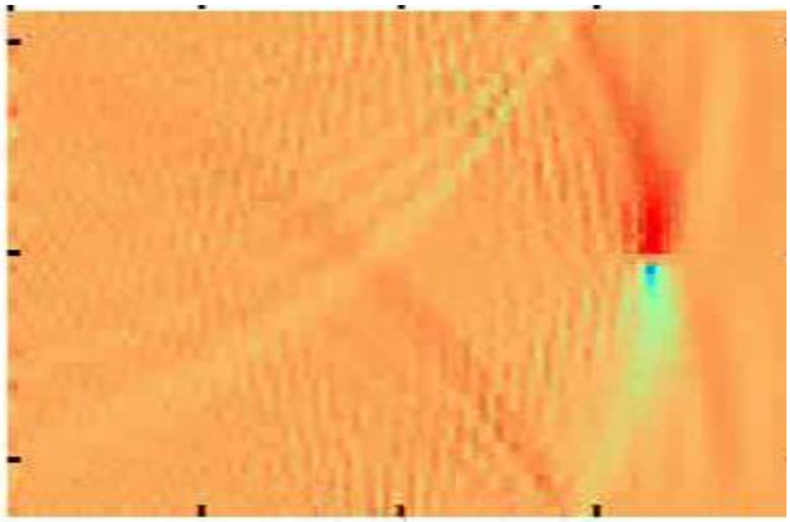


Figure 8. *Illustration of numerical Cerenkov. The particle's wakefields are visible as the main structure near the right edge. However, the short-wavelength "noise" behind the wakefield pattern requires noise reduction techniques.*

We have identified the state-of-the-art techniques for addressing the particle noise issues, and believe that we should employ such techniques, at least for the energy recovering calculation, which requires a generally lower level of noise than klystron and IOT simulations. Figure 9 illustrates the promise of one such technique, called the "perfect dispersion" algorithm, to prevent the noise and artificial dispersion of the particle wakefields.

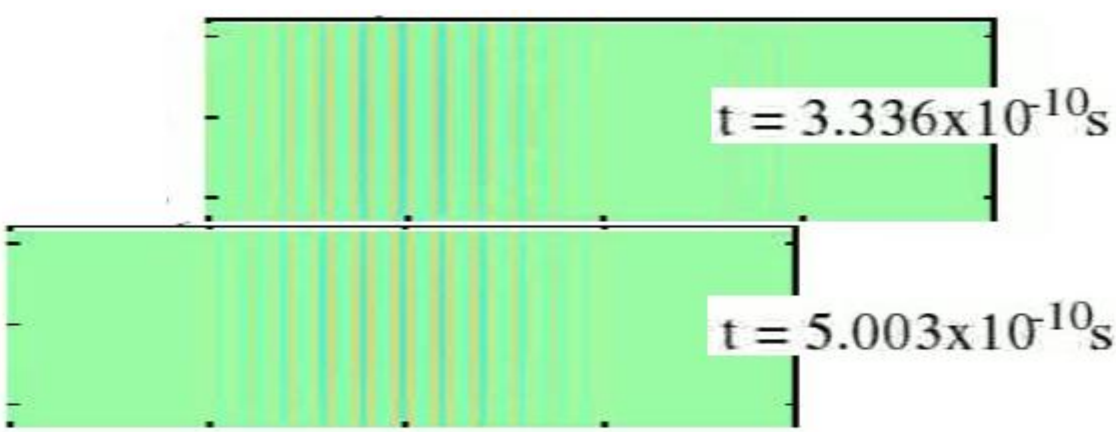


Figure 8. *Illustration from a simulation using the perfect dispersion techniques, which reduce particle noise by insuring exact-speed-of-light propagation along the beam direction. The figure shows a complex waveform at two different times. Perfect dispersion insures that the waveform has propagated intact without distortion or dispersion.*

Identification of Useful Improvements

A number of minor issues were identified in Phase I which, although not crucial to the overall feasibility of the simulations, nevertheless adds difficulty to the process.

For both klystron end-to-end analysis and depressed collector / beam dump simulation, one desires an active electric field boundary condition, which represents the fixed-voltage condition imposed by the external circuitry of the actual hardware. Presently, the boundary condition options are a passive fixed voltage boundary, or floating active voltage boundary condition. We will propose the addition of a voltage-feedback mechanism to the existing active boundary, in order to better represent the physical behavior of the electrodes in guns and collectors.

Gun and collector simulations must utilize realistic magnetic field profiles, which are often provided in the many different formats output by the magnet design codes. We will need to translate this information into HDF5 format that is used by the VORPAL software.

An IOT often contains a screen component, which electrically looks like a conductor, but which has transparency to particles less than 100%. Currently in VORPAL, it is possible to model a screen component with an effective 100% transparency. For improved realism, we would need to add a non-trivial transparency to existing capability in the screen component.

The energy recovery simulations will benefit from more automated particle statistics post-processing for such quantities as net energy and emittance as a function of time. We propose to greatly expand the existing particle history diagnostics capability, to include accelerator-design relevant quantities.

Identify Products developed and technology transfer activities

The technological results from this Phase I SBIR project were presented to the RF and microwave source community as a poster paper at the combined 2007 IEEE Pulsed Power and Plasma Science Conference (PPPS2007 / ICOPS2007), in Albuquerque, NM. The title of this paper was, “Design Calculations for high-space charge beam-to-rf conversion”.

Some of the software methodologies developed in the Phase I project, in particular the work with cavity modes, are now encoded in example input files and benchmarks for the VORPAL software, which is available to the public for a typical license fee, more information is available at the website: vorpal.txcorp.com. There were no patents derived from the Phase I work.

Computer Modeling

Details of the computer modeling are discussed the prior sections, including some published (refereed) references for algorithms. All simulations were run on Tech-X's local office-scale cluster.

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