Title of the accomplishment:

**Identification of the cause of beam breakup instabilities in a CEBAF accelerator upgrade using shape uncertainty quantification techniques**

The authors, groups, divisions and laboratories and/or departments and universities involved in the accomplishment:

**Volkan Akcelik, Kwok Ko, Lie-Quan Lee, Zenghai Li, Cho Ng, Liling Xiao (SLAC National Accelerator Laboratory, Menlo Park, CA 94025, USA)**

**F. Marhauser, C. Reece, R. Rimmer and H. Wang (Thomas Jefferson National Acclerator Facility, VA 23606, USA) and**

**Esmond Ng (Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA)**

A short description (one paragraph) of what was accomplished (i.e. what was discovered, invented, or proven):

**Beam Breakup (BBU) instabilities at well below the designed beam current were observed in the CEBAF 12 GeV upgrade of the Jefferson Lab (TJNAF) and beam excited Higher Order Modes (HOMs) with exceptionally high quality factor (Q) were measured in a prototype cryomodule (top right figure). A simulation effort was launched to study these HOMs and help identify the cause of the BBU. Under the support of the SciDAC ComPASS project, researchers at SLAC developed a shape uncertainty quantification tool with the goal to assess the sensitivity of the accelerator cavity parameters, such as frequency and Q, to changes in its dimensions. Using the measured values as inputs, the inverse problem was solved through an optimization technique to recover the cavity shape. The calculation revealed that the cavity with the very high Q values was 8 mm shorter (bottom left figure) than nominal length which was considerably beyond machining tolerance limits. This deformation of the cavity shape was subsequently confirmed by experiment and identified as a fabrication error. In the deformed cavity the electromagnetic fields of the HOMs shift away from the HOM couplers resulting in significantly lower damping for some of these modes and accounting for the exceptionally high Qs found in measurement (bottom right figure).**

Explanation of the significance of this accomplishment (in layman's terms):

**The deformation of accelerator cavity introduced during fabrication may affect accelerator performance, and it is difficult to determine the actual deformed shape experimentally even with the availability of measurement data. Motivated by the puzzle of the CEBAF BBU, SLAC has developed the computational tools with supporting infrastructures and implemented it on NERSC computers to solve the shape uncertainty quantification problem using an optimization technique. Being able to predict the fabrication error which was confirmed with measurements, and explain the physics results is a significant accomplishment which can only be achieved by a collaboration between accelerator physicists, computer scientists and applied mathematicians as intended by SciDAC. It also underscores the importance of quality control for manufacture tolerances in cavity fabrication to ensure that a cavity installed into the accelerator will achieve its designed performance. Success in the effort provides evidence that the mathematical and computational basis for these large scale simulations are sound so that the similar approach can be applied to new challenging problems of this nature as they arise.**

The impact this accomplishment will have on the DOE mission in science, computing, energy, or the environment:

**Cavity design for accelerator research has long been a hardware prototyping undertaking based on the trial and error approach. With the advent of computers, computer-aided-design for accelerator cavity is now well established, first for 2D and now for fully featured 3D geometries. This has had a**

**big impact on accelerator R&D as cavities can then be designed much faster and with confidence while new ideas can be explored to improve cavity performance. The arrival of SciDAC has helped to establish the partnership between application scientists and computational scientists in the quest for new discoveries using high performance computing. One SciDAC goal is the development of parallel computational tools that can advance the state of the art in simulation and modeling to benefit challenging applications. The success of applying a shape uncertainty quantification tool under the SciDAC ComPASS accelerator project to solve the BBU problem in the CEBAF 12-GeV Upgrade has clearly demonstrated the impact of SciDAC multi-disciplinary approach in solving a real-world challenging problem through scientific computing.**

Resources and approaches (facilities, computing resources, software, innovative approaches, etc.) used in this accomplishment:

**The shape quantification tool is posed as an inverse problem through a nonlinear least squared optimization method.  It was the first application of the optimization method to address a large-scale, realistic problem in accelerator science. Using measured parameters as inputs, the objective of the optimization problem is to minimize the misfit of the computed and measured responses to determine the deformed cavity shape. Each nonlinear iteration requires solutions of a forward eigenvalue problem and an adjoint problem, and evaluations of the inversion equations. The forward eigenvalue problem is solved using the finite-element electromagnetic eigensolver Omega3P. The solution of the linear systems in the forward and adjoint problems are obtained using direct solvers such as SuperLU and MUMPS.  The shape quantification tool used to solve the CEBAF BBU problem ran on the Cray XT4 supercomputers, Frankin at NERSC and Jaguar at NCCS.  A typical run used 256 cores and 37k CPU hours to obtain the optimized solution for the reconstruction of the deformed cavity from measured data.**

Interactions and role of university and laboratory collaborators involved in this work:

**The code development for and simulation using the shape quantification tool were carried out by accelerator physicists and computational scientists at SLAC, and the measured data of the CEBAF cavities provided by accelerator scientists at TJNAF. The interactions were extremely fruitful that the feedback provided by one group significantly enhanced progress in the other. For example, the findings obtained by SLAC scientists provided insights for TJNAF scientists to perform the relevant measurements to confirm the cause of the BBU problem. The work also benefitted from collaborations with applied mathematicians at LBNL under TOPS in developing a solver for saddle point linear systems essential for the solution of the adjoint problem.  This project has provided the classic example in which experiment, theory and computing were all engaged in a common effort to solve a challenging problem in accelerator physics.**

Funding and computing program(s) that supported this work:

**DOE: ASCR, BES & HEP Divisions under contract DE-AC02-76SF00515**
**DOE: NERSC allocations m349 and m778, and INCITE award aph001 at NCCS**

Publication(s) to cite when referencing this accomplishment:

**V. Akcelik et al., “Shape Determination for Deformed Electromagnetic Cavities”, J. Comput. Phys., 227, 1722 (2008).**

**Z. Li et al., “Analysis of the Cause of High External Q Modes in the JLab High Gradient Prototype Cryomodule Renascence”,SLAC-PUB-13266, Jun 27, 2008. 15pp**.

What future efforts associated with and/or motivated by this accomplishment are proposed and why?:

**One proposed effort motivated by this accomplishment is the incorporation of the shape uncertainty**

**quantification tool into the set of parallel EM codes under development at SLAC which can then be further improved and used by the accelerator community. Such a capability can greatly benefit cavity builders across the DOE accelerator complex when cavity deformations can be predicted by applying this tool to measured data and obtain information on fabrication errors. This can help identify potential problems in accelerator operation and avoid costly repair. Another proposal is the extension of the optimization method to include particle beam effects to model electron guns and improve their designs. The development of this capability is challenging because optimization involving PIC simulation is very demanding. However the payoff could be significant as almost all particle accelerators start with a gun whose performance is critical to the entire machine.**

## Further Instructions

To standardize the input, use 1-inch margins all around and 10-point Times New Roman font.

Include one or more images to illustrate the accomplishment, and 1 ppt slide that summarizes it.