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Title: Engineering Innovation to Reduce Wind Power COE

Author(s): Curtt N. Ammerman

Intended for: Meeting with DOE Wind & Water Program Office
Washington, DC
January 12, 2011

Los Alamos
NATIONAL LABORATORY
EST. 1943

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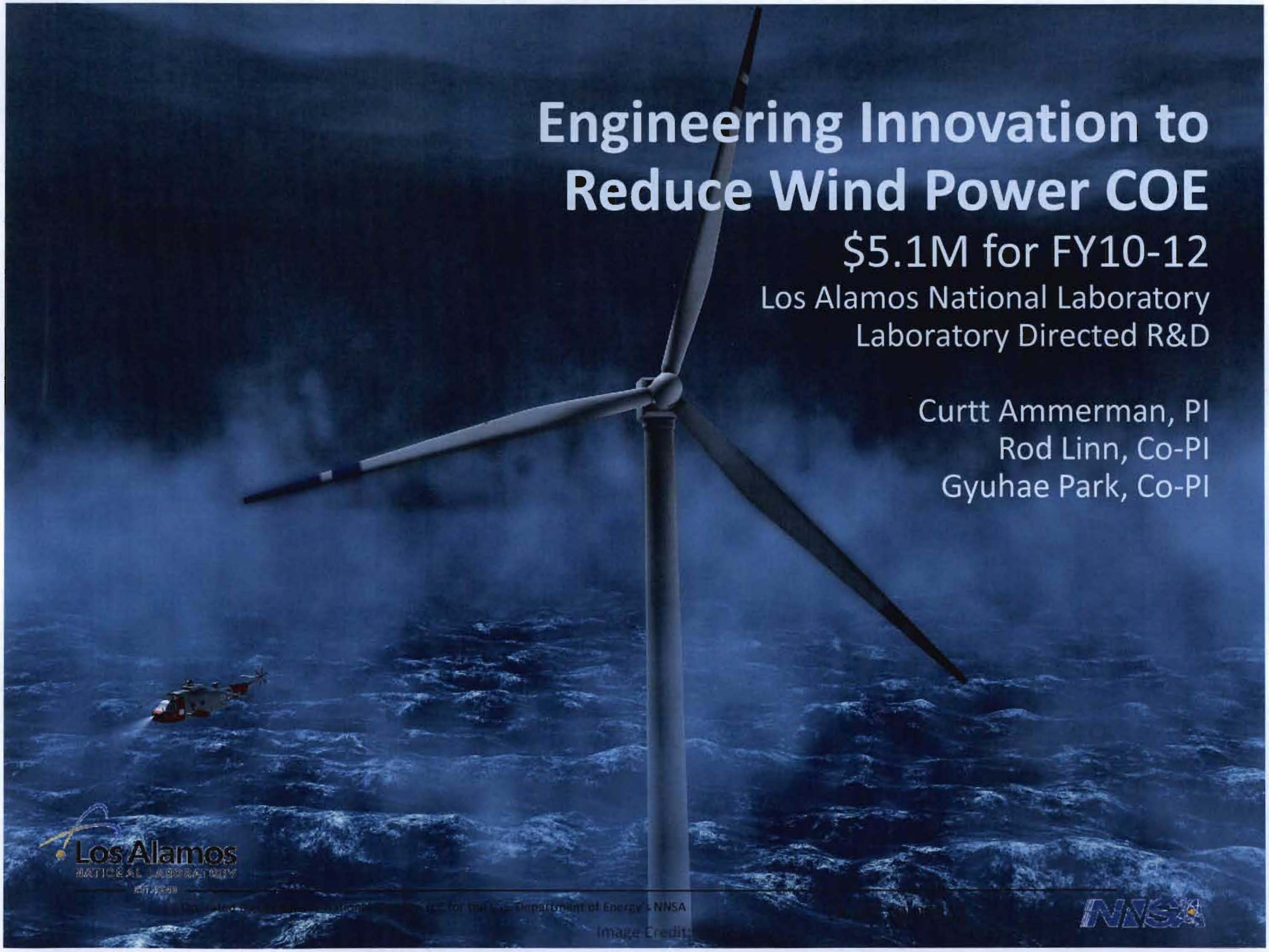
Title: Engineering Innovation to Reduce Wind Power COE

Speaker: Curtt Ammerman, Los Alamos National Laboratory

Abstract: There are enough wind resources in the US to provide 10 times the electric power we currently use, however wind power only accounts for 2% of our total electricity production. One of the main limitations to wind use is cost. Wind power currently costs 5-to-8 cents per kilowatt-hour, which is more than twice the cost of electricity generated by burning coal. Our Intelligent Wind Turbine LDRD Project is applying LANL's leading-edge engineering expertise in modeling and simulation, experimental validation, and advanced sensing technologies to challenges faced in the design and operation of modern wind turbines.



Engineering Innovation to Reduce Wind Power COE

$5.1M for FY10-12

Los Alamos National Laboratory
Laboratory Directed R&D

Curtt Ammerman, PI
Rod Linn, Co-PI
Gyuhae Park, Co-PI

Why Wind R&D at Los Alamos

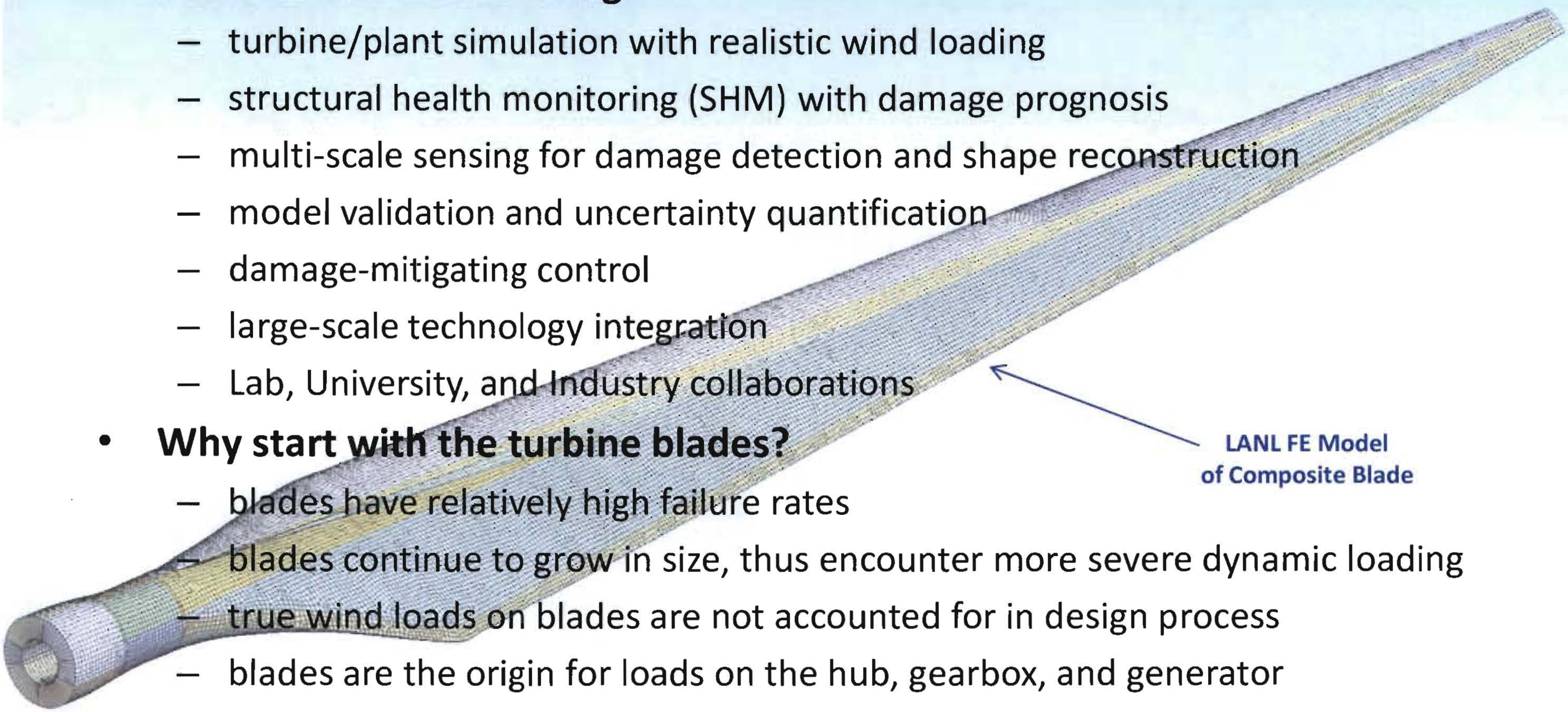
- We are uniquely positioned to contribute
  - **wind turbine and plant simulation**
  - **structural health monitoring**
  - **model validation and verification**
  - **large-scale technology integration**

- We complement DOE's wind energy strengths
  - **LANL**: computational modeling and multi-scale sensing
  - **SNL**: blade design technology and system reliability
  - **NREL**: blade testing, turbine design tools, and system integration

- We are building collaborative alliances
  - **SNL, NREL, UMass, U of Colorado, UC San Diego, Clemson, Iowa State, ASU**

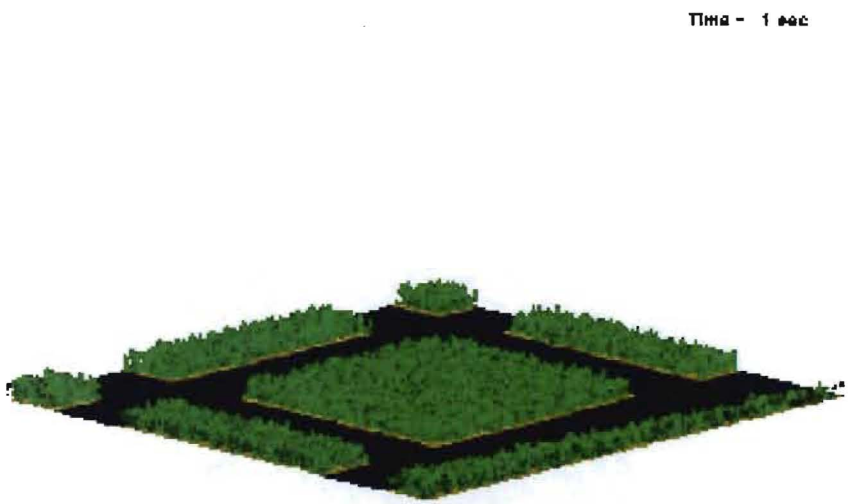
Our Research Is Centered On Turbine Blades

- **We have a comprehensive engineering R&D program focused on wind turbines that is delivering**
  - turbine/plant simulation with realistic wind loading
  - structural health monitoring (SHM) with damage prognosis
  - multi-scale sensing for damage detection and shape reconstruction
  - model validation and uncertainty quantification
  - damage-mitigating control
  - large-scale technology integration
  - Lab, University, and Industry collaborations
- **Why start with the turbine blades?**
  - blades have relatively high failure rates
  - blades continue to grow in size, thus encounter more severe dynamic loading
  - true wind loads on blades are not accounted for in design process
  - blades are the origin for loads on the hub, gearbox, and generator

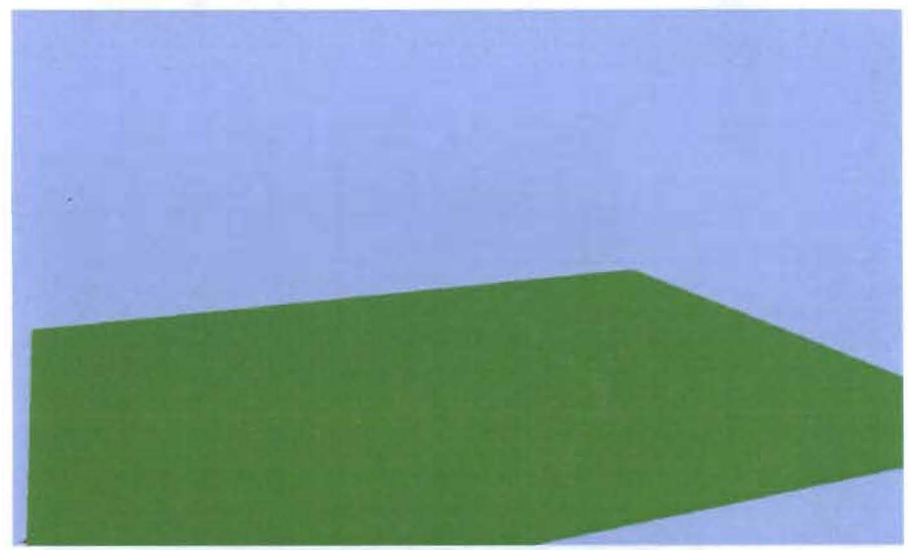


WindBlade: LANL's Turbine and Plant Simulation Code

- Couples R&D 100-winning HIGRAD/FIRETEC with LANL's new turbine/wind interaction modeling technique, **WindBlade** (*patent pending*)
- Provides capability to study realistic wind interactions with rotating turbines
  - fully compressible atmospheric hydrodynamics code
  - Lagrangian tracking scheme that **accounts for 2-way feedback between winds and moving solid objects**
  - resolves complex environments: topography, unsteady winds, severe weather, solar heating/unstable mixing
  - aeroelastic, fluid-structure interaction (FSI) capability will be able to extract dynamic loads on blades and towers



***HIGRAD/FIRETEC* Wildland Fire Simulation**



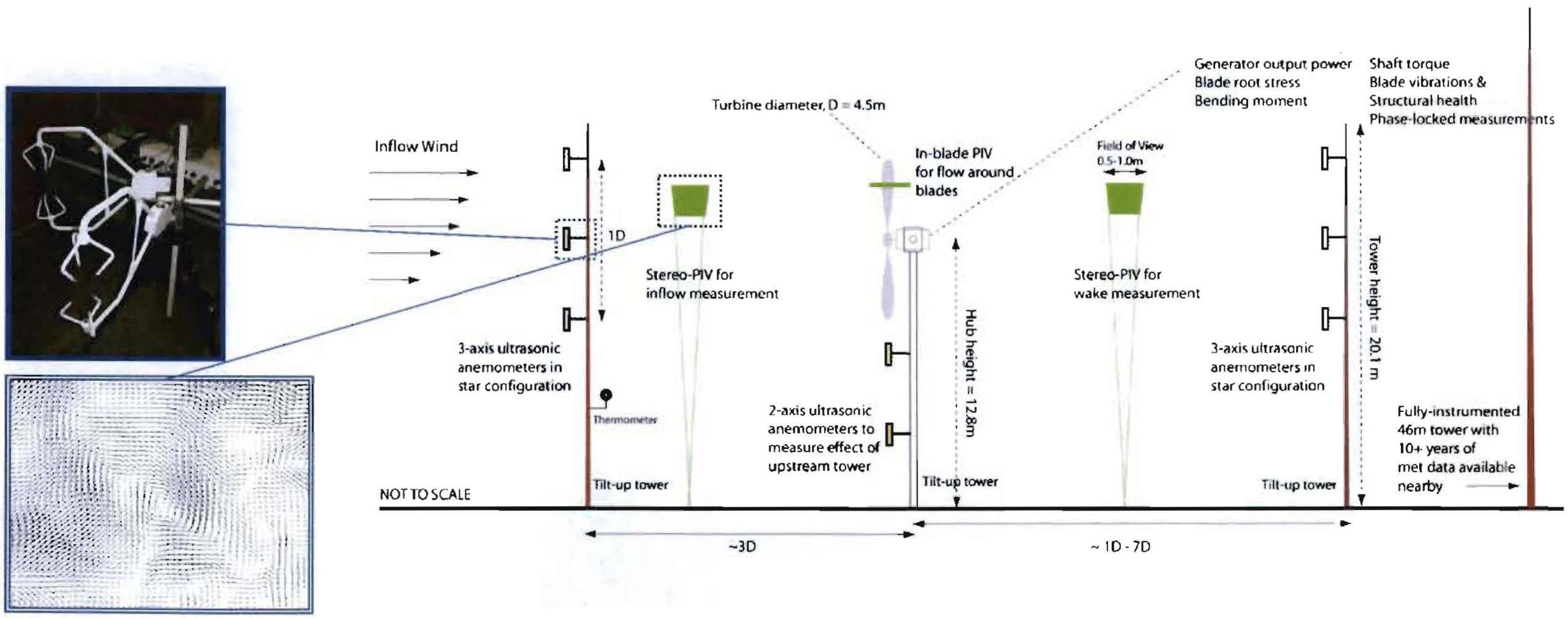
***WindBlade* 9-Turbine Simulation Showing Turbulence-Induced Vorticity**

LANL Developing High-Quality Aero Validation Datasets: Characterizing Inflow, Near-Blade, and Wake Regions

Wind Tunnel Experiments
- Laminar, turbulent inflow under yaw
- 0.2m diameter; 2-20 m/s
- PIV, hot-wire, LDV

New Diagnostic Techniques
- In-blade PIV, LF-PIV
- 2m x 2m PIV (scalable to 20m x 2m)
- Fiber-optic routing through blades: PIV around blade boundary layer through entire revolution

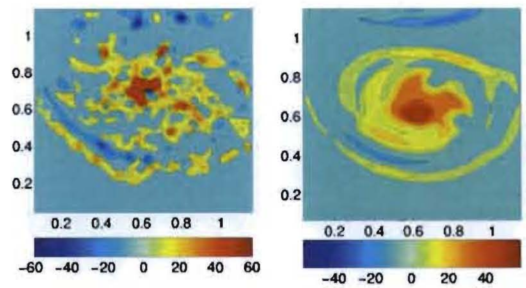
First-of-a-Kind Field Experiments
- 4.5m and 20m diameter turbines
- PIV, CSAT3, RM Youngs, Met-tower, power meter, strain gauge
- Integrated experimental datasets: aerodynamic, structural, and power



LANL Weapons V&V Expertise Is Applied to WindBlade Wind Turbine Simulation Code

- Nuclear weapons stockpile must be maintained without testing therefore LANL relies heavily on HPC to simulate nuclear weapon performance
- Verification and Validation (V&V) is a quantitative bridge between physics models, simulation, experiment
  - **Verification**: Solving the equations correctly (i.e. *get the math right*)
  - **Validation**: Solving the correct equations (i.e. *get the physics right*)

Gas Shock Tube Experimental Images (top) Calculations using RAGE code (bottom)



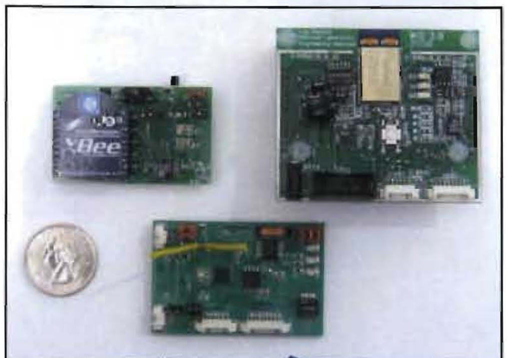
Vorticity Values for Experiment (left) and RAGE Calculation (right)

V&V Provides Confidence for Simulation Extrapolation

Anticipating Failure, Rather Than Reacting To Failure

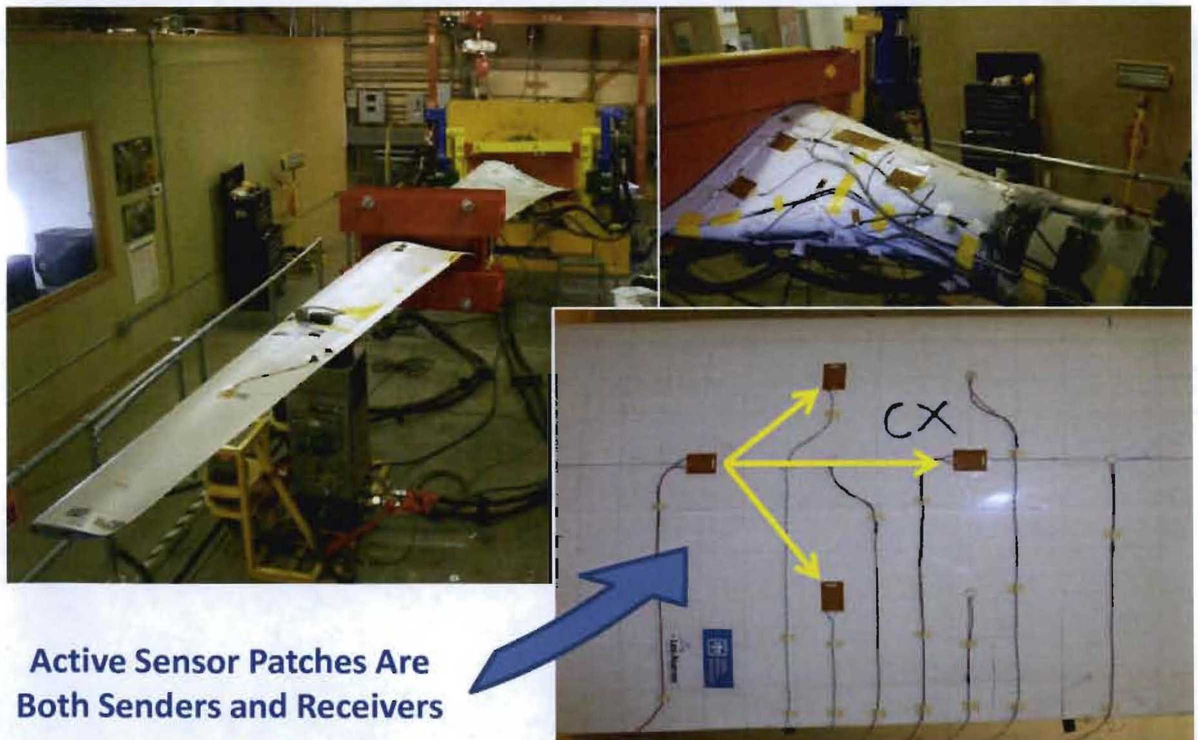
- We are developing low-cost sensing systems to monitor blade health
- Embedded in each blade, this system will
  - Identify structural damage and monitor its progression
  - Predict remaining useful blade life

LANL Wireless Sensor Nodes
(No Wires = No Lightning Rods)



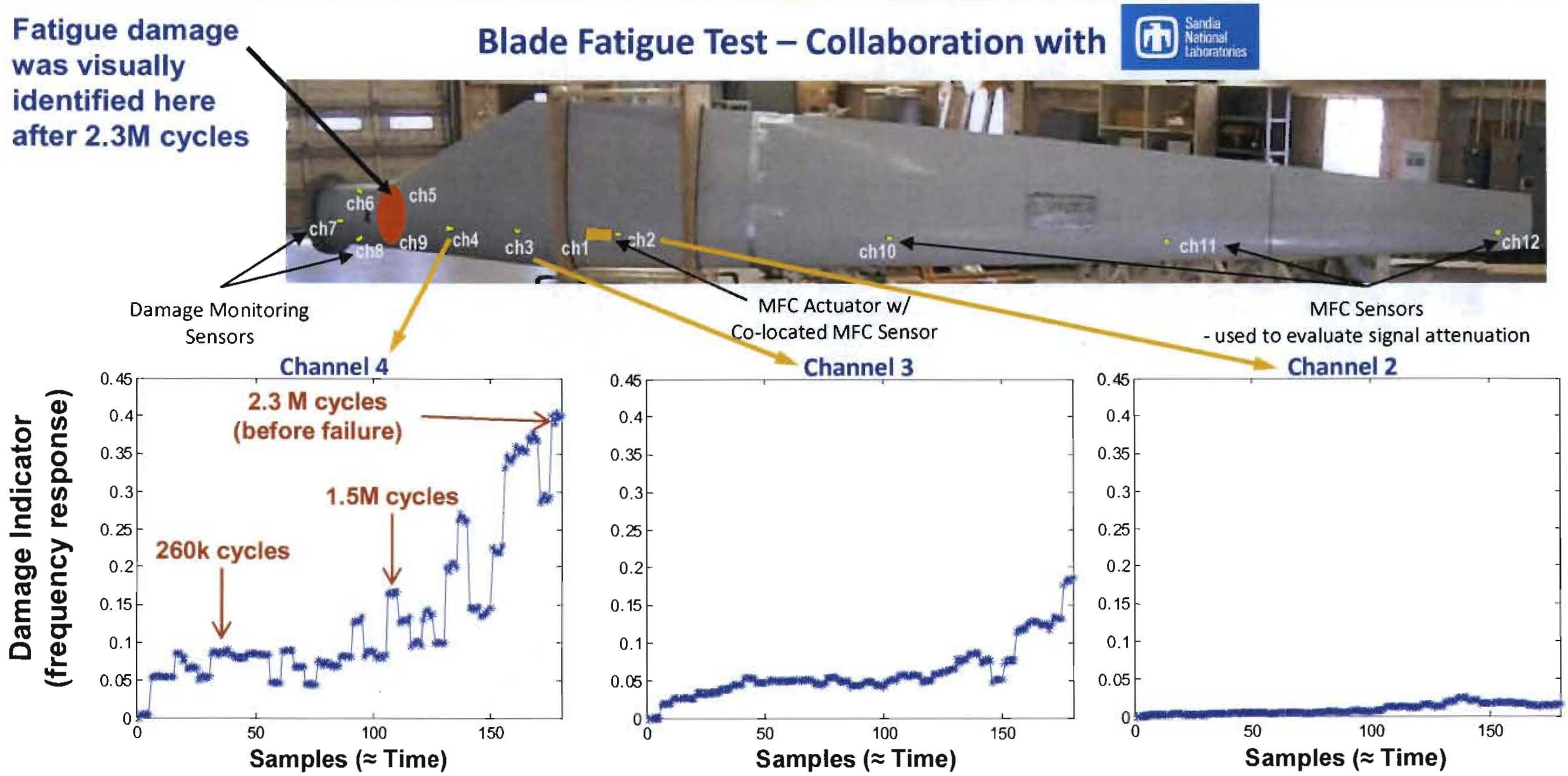
Energy Harvesting
(No Batteries)

We Are World Leaders in Structural Health Monitoring



Active Sensor Patches Are Both Senders and Receivers

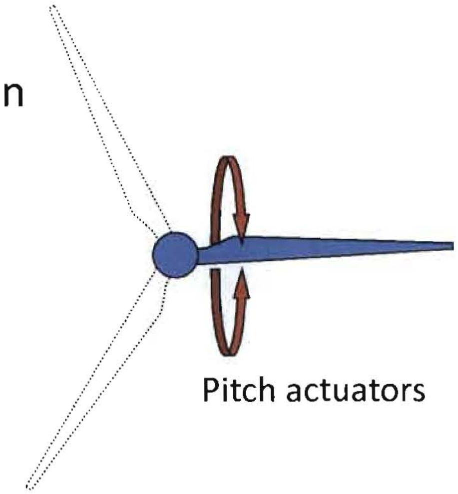
Active Sensing Detects Growing Crack In Blade!



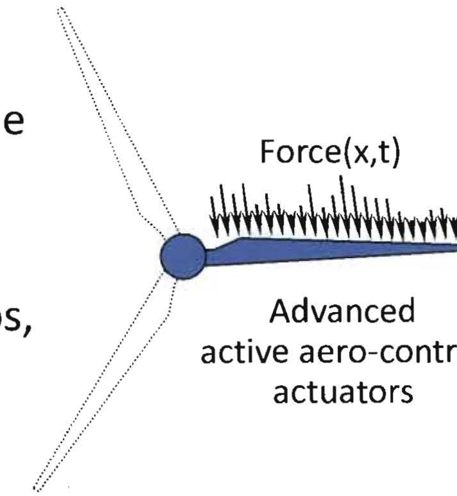
- We proved damage and damage progression are detectable with our techniques
- We characterized transmission loss in composite blade as a function of frequency (100Hz - 30kHz)
- In our next fatigue test, we focus on identifying **location** and **severity** of damage

Damage-Mitigating Control Keeps the Blades Spinning

- **Today's Turbines: Do the best we can with pitch control**
  - Maximize performance while minimizing damage progression
  - Couple damaged system state with damage accumulation model to develop control laws
  - Demonstrate on full-scale turbine at NREL CART facility →



- **Future Turbines: Re-configure blade control on the fly**
  - Adjoint-based optimization employing LANL **WindBlade** code
  - Allows gradients of a cost function to be calculated with respect to time-varying and spatially-varying forces
  - Assessing advanced actuation concepts (e.g. twist, microtabs, active flow control) before paying for hardware



LANL Technologies Will Reduce COE for Offshore Wind

WindBlade HPC Code

- single- and multi-turbine simulation
- realistic turbulent wind loading
- turbine-turbine interaction via rotating turbulent wakes and wake recovery
- aeroelastic structure
- capability to add ocean wave loading

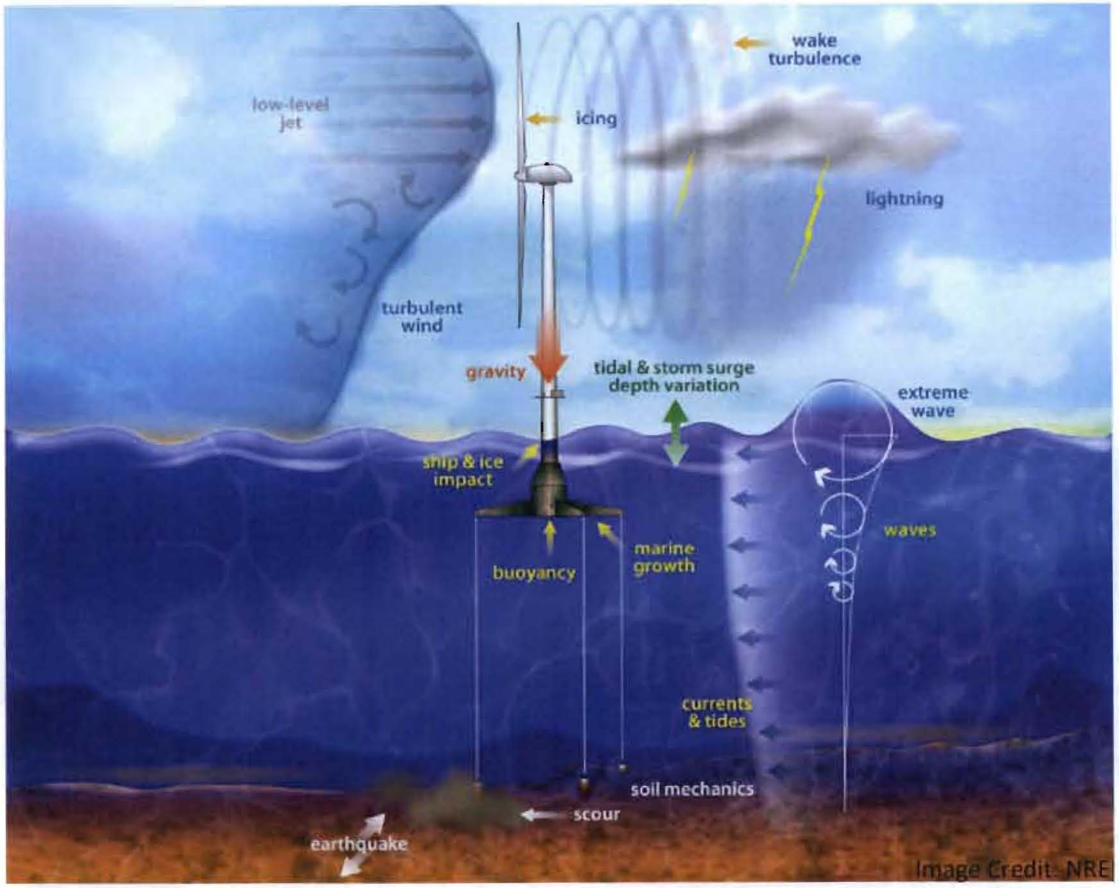
Multi-Scale Sensing

- blade structural health monitoring
- damage detection and shape reconstruction
- damage prognosis for prediction of remaining useful life
- low-cost, self-powered system
- capability to extend to gearbox/drivetrain

Aerodynamic Datasets for Code Validation

- new diagnostic techniques
- wind tunnel experiments
- first-of-a-kind field experiments

Damage-Mitigating Control



LANL Wind Collaborations

- **SNL**
  - Joint DOE contract for rotating, in-blade PIV experiment (Dale Berg and Matt Barrone)
  - Tested our sensing hardware and software on their sensor blade fatigue test (Mark Rumsey and Jon White)
  - They will test their hardware on our CX-100 blade fatigue test, and our 20m-dia turbine test
- **NREL**
  - Validating the wake structures produced in our simulations (Neil Kelley and Pat Moriarity)
  - Incorporated TurbSim into WindBlade
- **UMass Lowell**
  - Supporting DOE contract on Effects of Defects by providing "defect free" fatigue test (Chris Niezrecki, Pete Avitabile)
- **University of Colorado**
  - Validating our simulations with their LIDAR data; looking forward to measuring/modeling flow around full-scale turbine at NWTC (Julie Lundquist)
- **UC San Diego**
  - Developing adjoint version of fluid-structure interaction (FSI) code for advanced blade control studies (Yuri Bazilevs)
- **Clemson**
  - Developing V&V and uncertainty quantification techniques for blade finite element models (Sezer Atamturktur)
- **Harvey Mudd College**
  - Senior design project: numerical and experimental project with residential class turbine
- **Iowa State University** (in discussions)
  - Focusing on the turbine induced flows and the impacts on surrounding microscale weather (Eugene Takle)
- **Arizona State University** (in discussions)
  - Combining their LIDAR and our PIV measurements on our 4.5m- and 20m-dia turbine tests (Ron Calhoun)
- **Luna Innovations** (in discussions)
  - Incorporating their fiber optics sensors in our 9m blade for our 20m-dia test

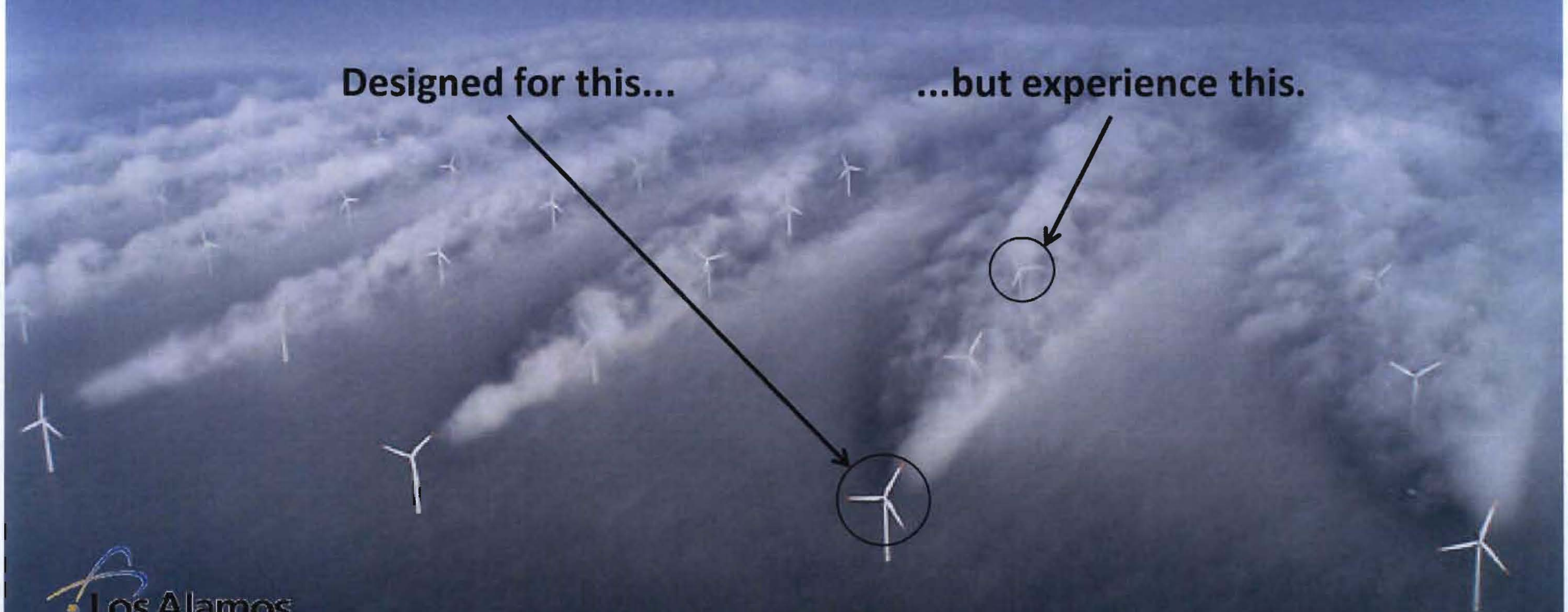
Los Alamos Dynamics Summer School

- Proactive approach to training and recruitment of top students through an intense, 9-week summer school program
- Program goal: Get top US-citizen engineering undergraduates enrolled in graduate school
  - Average GPA of these students: 3.8
  - Approx. 125/150 have gone on to grad school
  - 18 have completed their Ph.D.s
  - LANL has hired 14 Staff Members from this program
- Recent wind energy-related projects:
  - Structural Health Monitoring of a Floating Offshore Wind Turbine (2010)
  - Vibration Testing and Structural Damage Identification of Wind Turbine Blades (2010)
  - Structural Damage Identification in Wind Turbine Blades using Piezoelectric Active Sensing (2009)
  - Energy Harvesting to Power Sensing Hardware Onboard a Wind Turbine Blade (2009)
  - Real-Time Dynamic Measurements of a Wind Turbine Rotor Blade using Modal Filtering (2008)

Backup Slides

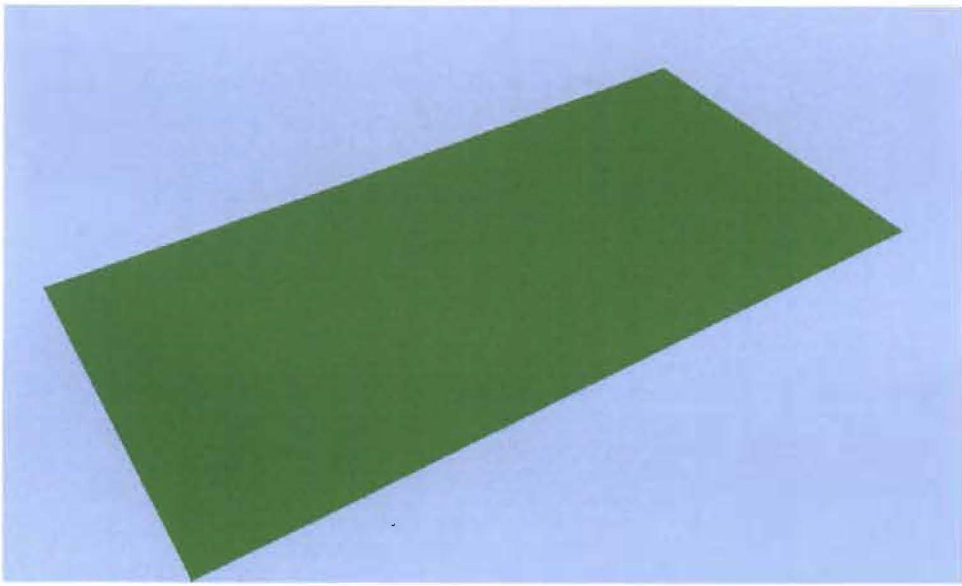
DOE's Goal: Reduce O&M Costs by 40%

- Wind power currently costs 5-to-8 cents per kilowatt-hour, which is more than twice the cost of electricity generated by burning coal
- Wind turbines are designed to last 20 years but fail on average 2-3 times per year during their first 10 years of operation



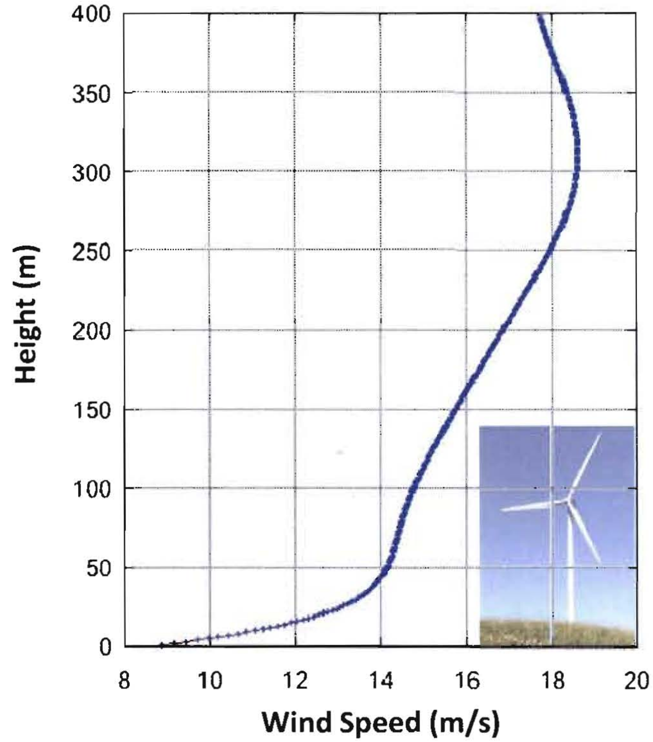
"Smooth Air" Isn't So Smooth

Turbulent Inflow Generated by NREL's TurbSim Code
(Domain is 1.7 km x 0.85 km)



Collaboration With NREL Provides Inflow Boundary Condition

Mean Velocity Profile



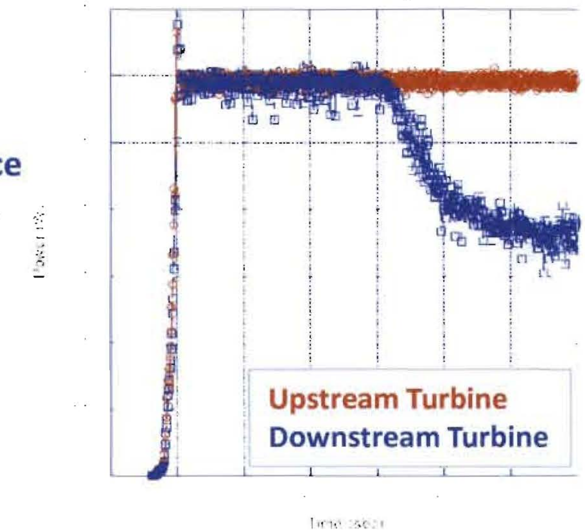
It Is Critical to Get Turbulence Right

[redacted]

Unresolved, Isotropic Turbulence

⟷

Power Output



With TurbSim: Resolved Turbulence

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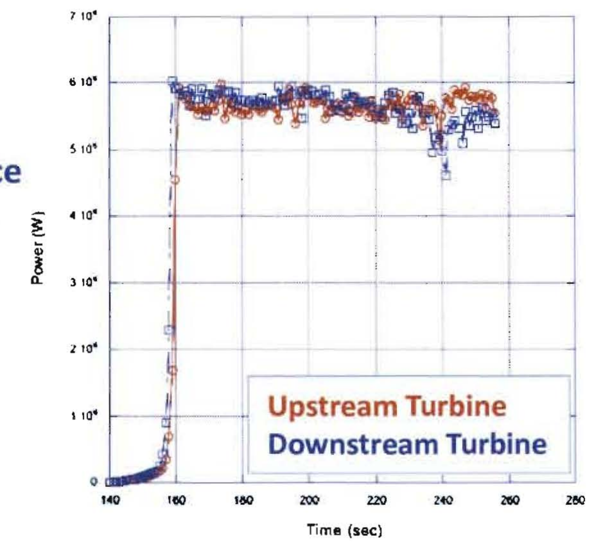
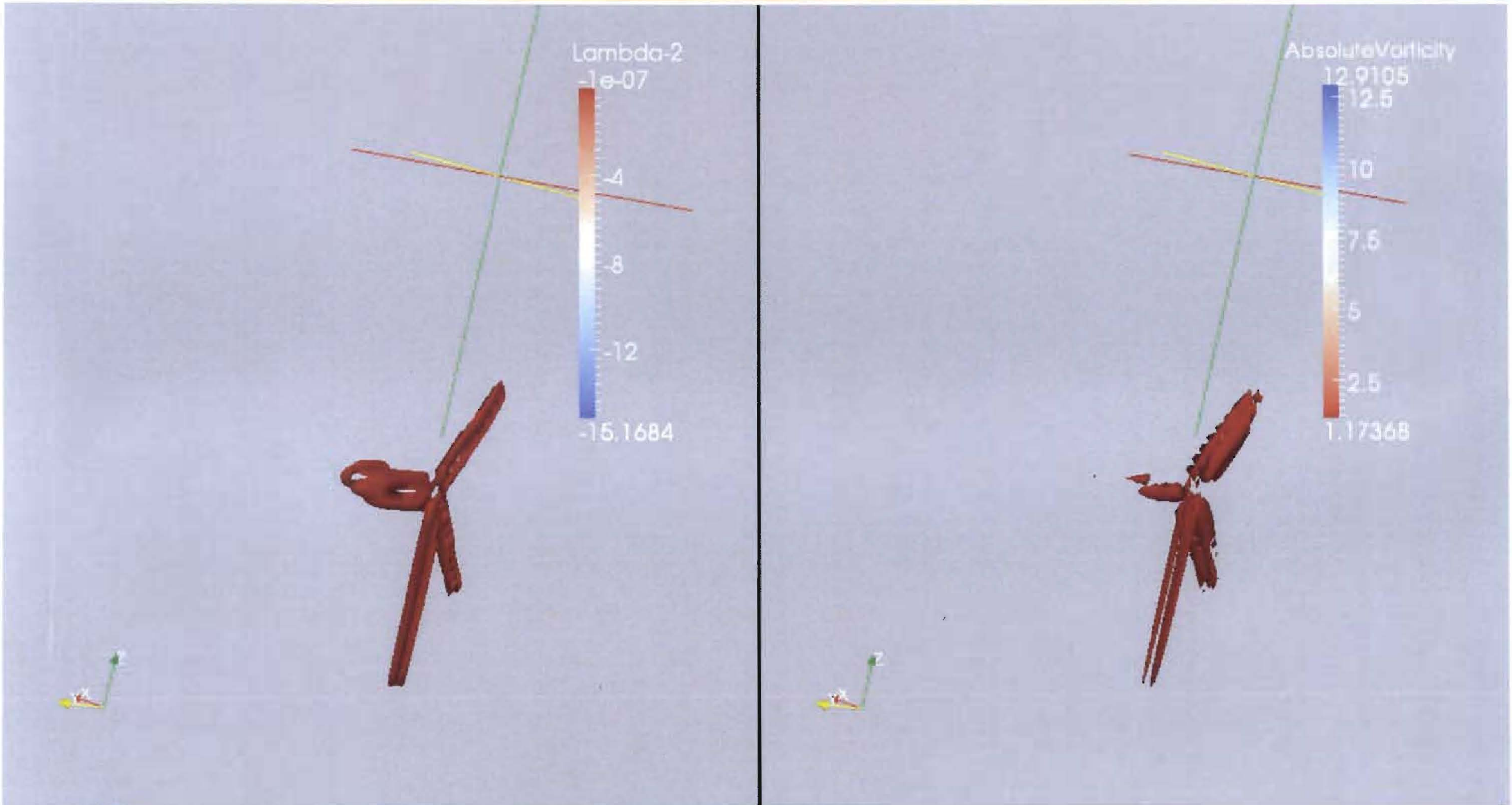


Data Interrogation and Visualization – It's Not Just the Simulation, We Need to Extract the Results

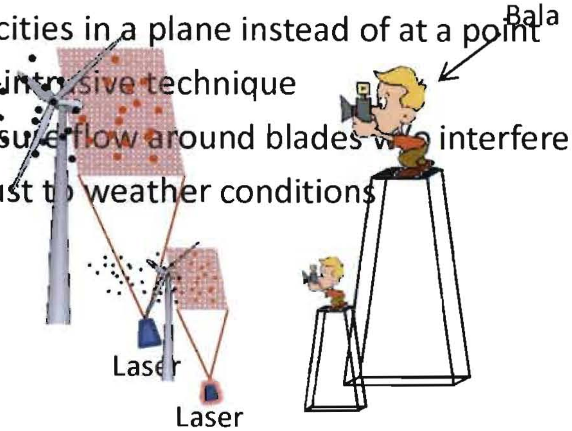


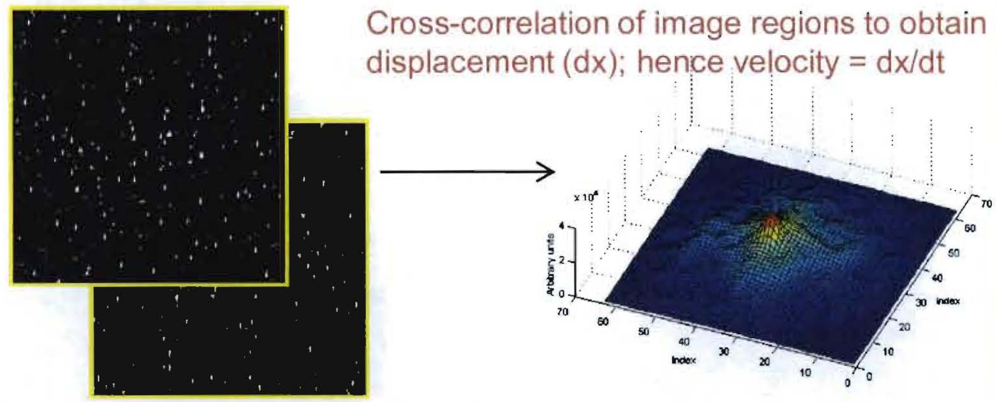
A New Diagnostic to Measure Detailed Flows Around Wind Turbines:
Large-Format Particle Image Velocimetry (LF-PIV)

Advantages

What is PIV?

- Excellent spatial resolution
- Velocities in a plane instead of at a point
- Non-intrusive technique
- Measure flow around blades w/o interference
- Robust to weather conditions

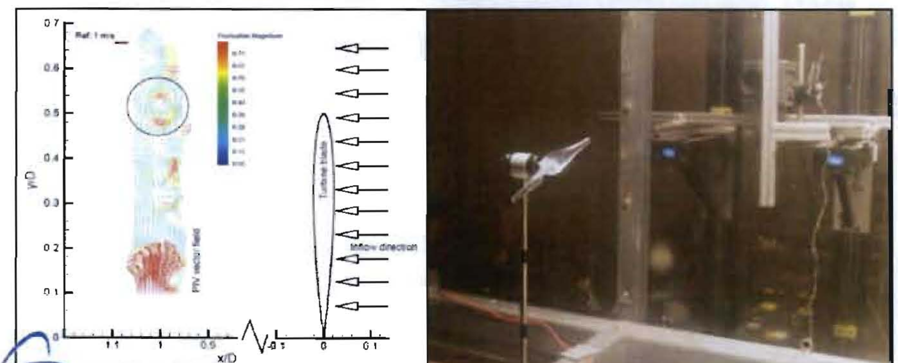




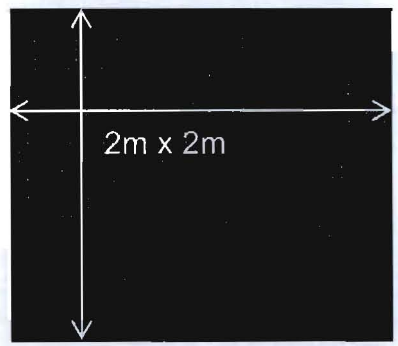
Cross-correlation of image regions to obtain displacement (dx); hence velocity = dx/dt

Two images separated by a short interval of time (~1-1000 micro seconds)

Turbulent Vortices Measured in Wind Tunnel at New Mexico State University

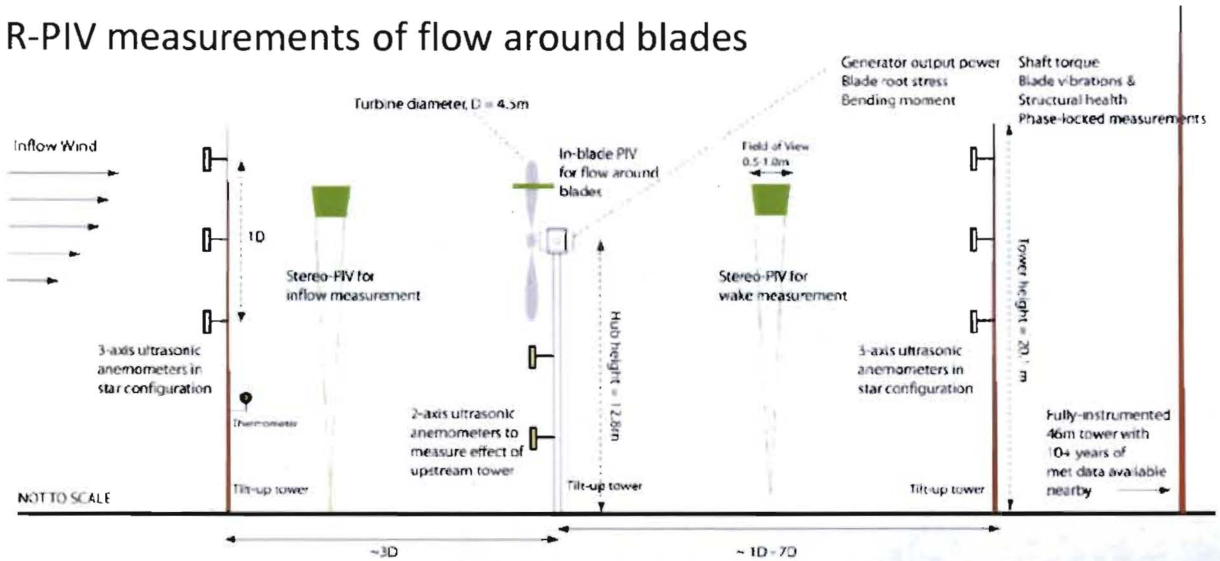


We have demonstrated the <u>largest field of view</u> and <u>largest stand-off</u> for conventional PIV in the world so far!



High-Risk, High-Payoff Path to Improved Design Tools

- FY11: Fully instrumented field test of 4.5m-diameter turbine at LANL to include:
  - Stereo LF-PIV measurements of inflow and outflow
  - In-blade R-PIV measurements of flow around blades



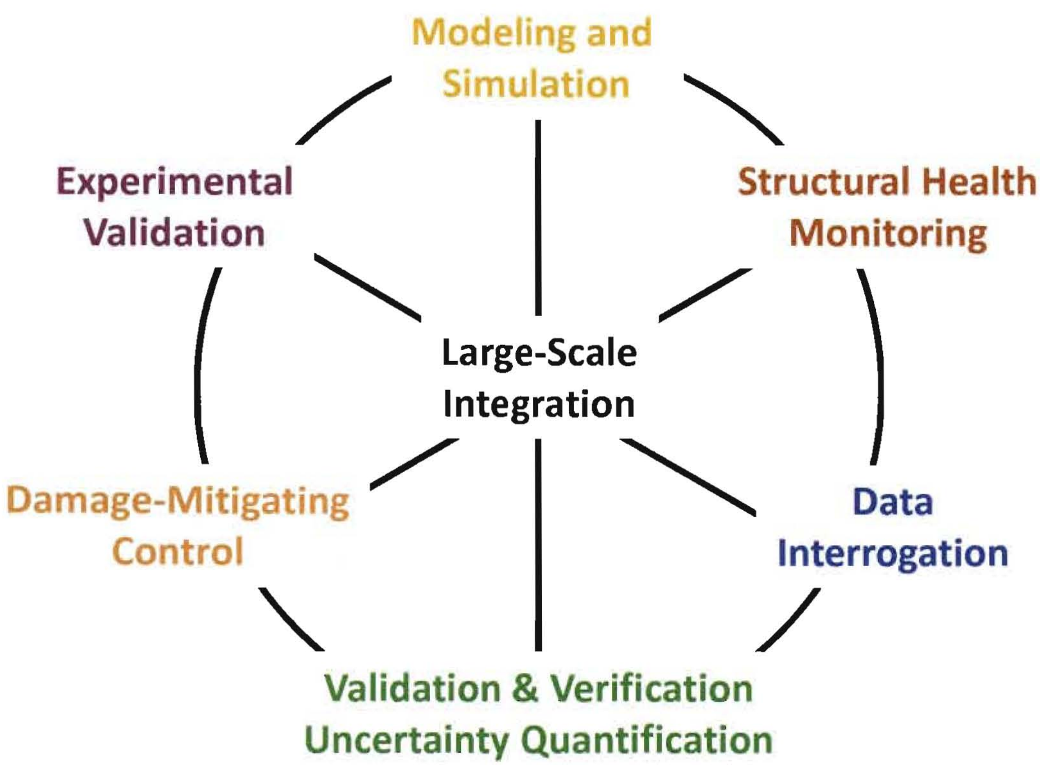
- FY12: In-blade R-PIV measurements on 20m-diameter turbine with LANL 9m blades

Our Project Culminates In Full-Scale Flight Test of Relevant Structures and Flowfields

- Full range of instrumentation on three, 9-m blades
  - **Blade 1**: High-frequency SHM techniques to monitor blade transition region, and bolted joints at blade root
  - **Blade 2**: In-blade, rotating PIV system
  - **Blade 3**: Low-frequency sensing (e.g. fiber-optic, camera-based)
  - **All Blades**: Strain and acceleration sensors for shape reconstruction and energy harvesting
- Tower-mounted sensors to monitor upstream and downstream flow conditions
- Results fed into prognostic analyses and visualization algorithms to validate WindBlade and FE codes
- Proof of concept for validating embedded sensing

Multi-Disciplinary Engineering Research Team

Mutually Reinforcing National Security Missions



Modeling:
- **R. Linn (EES-16) - Lead**
- **C. Ammerman (AET-1) - PI**
- G. Ellis (AET-1)
- E. Koo (EES-16)
- D. Luscher (W-13)

Sensing:
- **G. Park (INST-OFF) - Lead**
- T. Clayter (AET-6)
- K. Farinholt (AET-1)
- E. Raby (ISR-3)

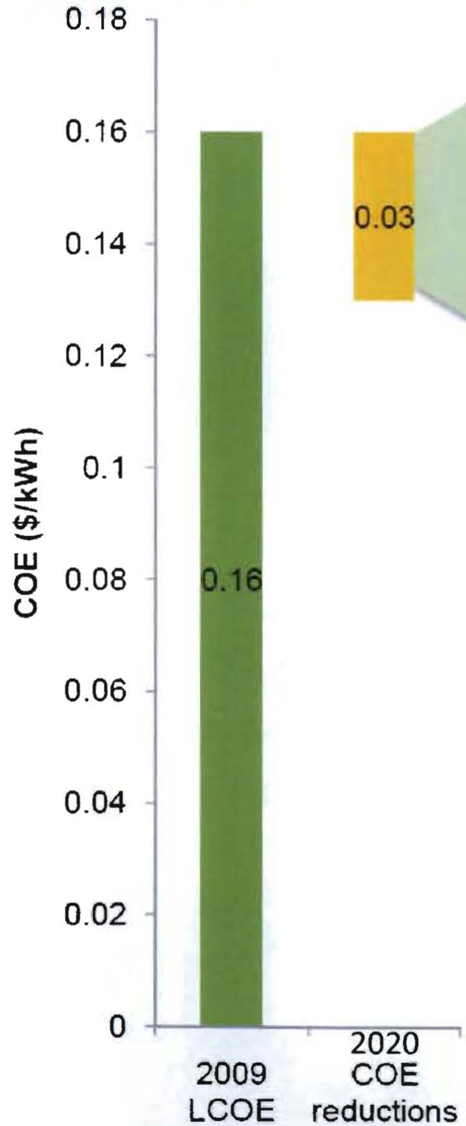
Prognosis/Data Management:
- **F. Hemez (X-3-LGRN) - Lead**
- J. Ahrens (CCS-1)
- D. Hush (CCS-3)

Controls:
- **M. Bement (X-3-LGRN) - Lead**

Experimental Validation:
- **K. Farinholt (AET-1) - Lead**
- B. Balasubramaniam (P-23)

Offshore R&D Opportunities

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy



Challenges

High capital costs
Marinization
Foundations & infrastructure
Installation & staging facilities
Reliability & maintenance

Benefits

Lower capital costs
Innovative turbines & foundations
Reduced need for maintenance

Activities

Large component test facilities
Design codes & tools development
Foundations & platforms R&D
Innovative turbine designs
Certification & standards
Marine grid interconnection R&D
Resource & design condition characterizations

Partners

National laboratories
Federal agencies: MMS, NOAA, NCAR, FWS, DOD, DHS, ACOE
Turbine OEMs
Universities (U of Maine, U Delaware)
State agencies